An eye-hand movement Model for traffic complexity evaluation and monitoring enhancement for air traffic controllers

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**An Eye-Hand Movement Model for Traffic Complexity Evaluation and Monitoring
Enhancement for Air Traffic Controllers**

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SCHOOL OF MECHANICAL AND AEROSPACE ENGINEERING

2019

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Enhancement for Air Traffic Controllers

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SCHOOL OF MECHANICAL AND AEROSPACE ENGINEERING

A thesis submitted to Nanyang Technological University in partial
fulfilment of the requirement for the degree of

Doctor of Philosophy

2019

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

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Prof Lye Sun Woh

Authorship Attribution Statement

This thesis contains material from 2 papers published in the following peer-reviewed journals from 4 papers accepted at conferences in which I am listed as an author.

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The contributions of the co-authors are as follows:

- Prof Lye Sun Woh provided the initial project direction and edited the manuscript drafts
- Mr Jean-Philippe Pinheiro provided technical support in terms of the experimental setup and the use of the TopSky-HF system
- I prepared the manuscript drafts and analysed the data
- All the experiments and data collection were conducted by me in the Radar Simulations Lab, Air Traffic Management Research Institute (ATMRI).

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Abstract

Dynamic changes in the field of Air Traffic Management in recent years, coupled with the increasing use of automation and new concepts like 4-Dimensional Trajectory Based Operations (4D-TBO) are being investigated. It is therefore postulated that future Air Traffic Controller (ATCO) tasks would likely be dedicated to performing more tactical monitoring activities presented on radar displays with lesser communication with the flight crew under regular circumstances, changing the way how ATCOs operate. This brings about a new set of challenges to ATCOs, as current approaches to address issues related to an ATCO's tactical control activity both operationally and in training, remain limited, due to the lack of knowledge extraction and representation of this activity. This is seen in three different aspects, which are namely the lack of exploitation of shared information between the physical heterogeneous data capture systems with human operated functions; the inadequate representation of tactical air traffic complexity; and the shortage of methods in extracting and representing an ATCO's monitoring behaviour of the air traffic situation.

This research presents a new eye-hand movement model for traffic complexity evaluation and monitoring enhancement for ATCOs under radar surveillance. This eye-hand movement model seeks to integrate information from both dynamic radar and human data streams in real time, while being synchronous. To achieve this goal, efforts were devoted to addressing the three aspects of an ATCO's tactical monitoring behaviour, comprising the exploitation of shared information between human and system operated functions, the depiction of tactical air traffic complexity and the determination of an ATCO's perception and comprehension level.

An innovative measurement for the tactical monitoring activity of ATCOs, through the establishment of a data activity register frame, which allows for new knowledge extraction and representation in ATC, is first presented. Using a real time eye tracking system, an ATCO's monitoring behaviour is exploited and analysed by integrating the two sets of activity data (air traffic flight movements and eye tracking metrics) in a highly dynamic changing and synchronous manner in real-time with respect to both spatial and time frames, through the "Dynamic Data Alignment and Timestamp

Synchronisation Model”. Test results reveal that this model can synchronise the timestamp of the eye and dynamic display data, align both of these data spatially, while taking into account dynamic changes in space and time on a simulated radar display. This system can also distinguish and show variations in the monitoring behaviour of participants. As such, new knowledge can be extracted and represented through this innovative interface, which can then be applied to other applications in the field of electronic surveillance to unearth monitoring behaviour of the human surveillance operator.

A tactical complexity model, herein known as Conflict Activity Level (CAL), is then presented to depict tactical air traffic complexity. This is achieved by evaluating the likely aircraft flight shape profile based on its current and projected position and trajectory. From the flight shape profile, CAL values are computed based on instantaneous existing traffic numbers in the overall region or sub-regions of interest. The proposed complexity approach shows good agreement with other methods in terms of ranking the order of complexity of various air traffic scenarios and the key influencing factors contributing to conflict. In addition, the CAL – Separation Axes Theorem (CAL-SAT) model, capable of calculating the tactical complexity time profile between aircraft pairings based on their instantaneous flight information is also presented. Using this model, the dynamic traffic flow characteristics of the aircraft and the network characteristics of its projected tactical complexity across time can be achieved mathematically. This could assist ATCOs in the adoption of appropriate tactical control strategies. Application of the CAL-SAT model to two realistic ATC situations highlights the different possible tactical control strategies that can be adopted by ATCOs. Better task prioritisation, time management and greater certainty in the deployment of tactical control strategies by ATCOs were observed. Furthermore, watch managers and airspace designers could also benefit, through proper allocation and duration of shift duties assigned to respective ATCOs and the consideration of tactical complexity while designing the airspace respectively.

Three eye signatures that combine both eyeball and hand movement of an ATCO are presented. These signatures seek to capture and evaluate the perception and comprehension level of ATCOs for the different tactical monitoring activities. The

aligned fixation peak signature, fixation-click count signature and RCG time entropy signature are able to determine the crossing monitoring, aircraft frequency switch and generic flight path monitoring behaviour of ATCOs respectively. Differences in the monitoring behaviour are observed between expertise level and also between the characteristics of these different activities. Test results show that participants with more experience are more likely to exhibit aligned fixation peaks in the crossing monitoring activity as well as more consistent in exhibiting RCGs on the aircraft for the generic flight path monitoring activity. As such, these signatures can therefore be used to distinguish the monitoring behaviour of participants across different expertise level and also for assisting ATCOs in their tactical monitoring tasks under various circumstances. For the aircraft frequency switch activity, test results also show that the action of fixation-click is noticeable for participants for both ‘UCO’ and ‘TOC’ commands. As a result, alerts can be triggered operationally when ATCOs fail to perform at a specified level and the training of prospective ATCOs can thus be evaluated more objectively by instructors. This would pave the way for new operational standards and training methods to be developed in future.

Lastly, the eye-hand movement model is evaluated by integrating the traffic complexity and corresponding eye signatures synchronously, to deduce the likely strategies that ATCOs deploy in managing their tactical monitoring activities. For activity of aircraft crossing with potential conflict, test results suggest that the expert participant exhibited the aligned fixation peak signature for the purpose of maintaining vertical separation early and to keep awareness of the aircraft pair-in-crossing. For the activity of generic flight path monitoring, test results suggest that the expert participant likely deploys the strategy of monitoring an aircraft more often when a command needs to be issued. This could pave the way for alerts catering to an ATCO’s monitoring strategy to be developed operationally, thereby improving its effectiveness. In training, instructors could also provide curated feedback to the trainees in order to speed up the training process.

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List of Abbreviations

Abbreviation	Explanation
4D-TBO	4-Dimensional Trajectory Based Operations
ATC	Air Traffic Control
ATCO	Air Traffic Controller
ATM	Air Traffic Management
ATWIT	air traffic workload input technique
ADS-B	Automatic Dependent Surveillance Broadcast
BARS	Behaviourally-Anchored Rating Scales
CDM	collaborative decision making
CCO	continuous climb operations
CDA	continuous descent approach
CPDLC	Controller Pilot Data Link Communication
DA	Descent Advisor
EEG	Electroencephalogram
ECG	Electroencephalogram
ERAM	En-Route Automation Modernisation
FAA	Federal Aviation Administration
FIR	Flight Information Region
FMS	Flight Management Systems
HRV	Heart Rate Variability
HERA	Human Error Reduction in ATM Technique
HFACS	Human Factors Analysis and Classification System
ISA	Instantaneous Workload Assessment
NASA-TLX	NASA-Task Load Index
NM	Nautical Miles
NINA	Neurometrics Indicators for Air Traffic Management
OJTI	OJT Instructor
OJT	On Job Training
OE	Operational Errors
OFS	operator functional state
RNP	Required Navigation Performance
RA	Resolution Advisory
SASHA	SA for SHAPE

SASHA_L	SASHA on-Line
SASHA_Q	SASHA questionnaire
STCA	Short-Term Conflict Alert
SESAR	Single European Sky ATM Research Programme
SARS	situation awareness rating scales technique
SPAM	situation present assessment method
SA	Situational Awareness
SAGAT	Situational Awareness Global Assessment Technique
SART	Situational Awareness Rating Technique
SPD	spectral power density
SMEs	Subject Matter Experts
SVM	Support Vector Machine
T-SAFE	Tactical Separation Assured Flight Environment
TLI	Task Load Index
TAMR	Terminal Automation Modernization and Replacement
TA	Traffic Advisory
TCAS	Traffic Collision Avoidance System

1. Chapter 1 Introduction

1.1. Background

Major Air Traffic Management (ATM) developments in recent years have brought about changes in the field of Air Traffic Control (ATC). Two major programmes being initiated in the Single European Sky ATM Research Programme (SESAR) by Eurocontrol and the NextGen programme by the Federal Aviation Administration (FAA) that seek to better optimise the air traffic flow, improve efficiency and capacity as well as traffic safety within the airspace and air transport system.

One such emerging technological approach involves the adoption of 4-Dimensional Trajectory Based Operations (4D-TBO), where the flight trajectory of aircraft can be predicted in a timely, accurate and consistent manner. Flights would be expected to perform continuous climb operations (CCO) and continuous descent approach (CDA) so as to minimise delays. In addition, to better predict flight time more accurately, such an approach would lead to better flight trackability, savings in flight times and fuel burned as well as lesser controller intervention [1]. As a result, aircrafts are freer to fly on their own desired trajectories, creating a more complex air route structure with tighter separation standards [1-4].

Another recent major development is in the Flight Management Systems (FMS) where accurate information such as speed, altitude constraints and landing configuration are made known to both Air Traffic Controllers (ATCOs) and pilots [5]. Operations and procedures can be automated about two hours in advance in the pre-tactical phase, as the availability and access of such information is enabled. Hence, concepts like dynamic airspace re-sectorisation are being adopted [6] to account for changes in traffic flow catering to the workload of ATCO. Sectorless ATC is also another concept which can be adopted, where one ATCO is assigned to control an aircraft from entry point to the exit point of the combined single airspace, thus allowing aircraft preferred trajectory while increasing ATCO's efficiency, ensuring an even distribution of traffic load to ATCOs and increasing airspace capacity at the same time [7].

In the communication between ATCOs and pilot, one such technological improvement is seen in data communication, through the use of Controller Pilot Data Link Communication (CPDLC) [8], which is enabled via satellite based technology for Automatic Dependent Surveillance Broadcast (ADS-B) for the surveillance of air traffic and on-board navigation. In doing so, messages between ATCOs and pilots are displayed on a visual display. Such would result in the ATCO looking at both the radar screen and the CPDLC display, placing more emphasis on the tactical control and monitoring activity of ATCOs.

On the other hand, more automation aids were introduced in the field of ATC to help ATCOs with their current tasks. These have been developed to replace tasks like the acknowledgment of clearances between air crew and ATCOs at the fixed waypoints, which are deemed to be 'redundant' [9] and also to assist ATCOs in maintaining a predictable and orderly air traffic flow in the tactical control phase [10]. Examples of these automation aids are En-Route Automation Modernisation (ERAM), Terminal Automation Modernization and Replacement (TAMR), Final Approach Spacing Tool (FAST) and the Descent Advisor (DA) [11, 12], that seek to detect conflicts way in advance for better decision making, automate take-off and landing procedures with increased runway capacity and flight efficiency. Hence, it has been postulated that future ATCO tasks would likely be dedicated more towards monitoring and exogenous activities presented on monitor displays with lesser communication with the flight crew under regular circumstances [2, 13, 14]. Effective and efficient translation and interpretation of data on the screen display would therefore be of paramount importance [15].

Considering all the different technological advancements being applied to ATM, a change in traffic density and a change in traffic complexity is thus expected, as flight trajectories are more tailored to the capabilities of individual aircraft and aircraft are more freer to fly on their desired air routes on a daily basis [2]. Such efforts are aimed to cater to the future needs in ATM where global air traffic is expected to increase 4% annually to 2020 forecasted [16]. Hence, with a more complex air route design predicted in future and the increasing traffic density, aircrafts are expected to fly with tighter separation distance in a heavily congested airspace.

Current data also seem to highlight the need for more ATCOs in future [17], assuming the ratio between the number of aircrafts to ATCOs is maintained. More ATCOs would be then required and trained which could potentially give rise to a larger deviation of ATCO standards. In ATC, Air Traffic Controllers (ATCOs) who work using radar surveillance are required to monitor the aircraft as they fly through their airspace depicted on their radar screens, in their tactical monitoring activity. ATCOs will seek to create and maintain a mental picture of where the aircraft were on the radar screen [18]. Coupled with this shift in monitoring activities, technological and future concept changes in ATM, like 4D-TBO, CPDLC, dynamic re-sectorisation and sectorless ATC, a new set of challenges is presented to ATCOs where their current mode and pattern of operations would invariably be affected, together with a drastic change in mental model of the ATCOs, seen in the way they operate in the future. A change in training methods is also expected as the nature of ATCO tasks shift towards more active monitoring.

According to Endsley [19], a change in mental model of the ATCO will cause a shift in their attention having bearings on the efficiency and safety performance levels of the ATC. Case studies have shown that with more uncertainty and increasing traffic complexity, there would be negative consequences on an ATCO's performance and workload [20, 21]. This is for the present mental model of ATCOs may not be adequate to adapt and deal with the changes in activities, technologies and concepts. Instead new mental models may need to be established. This problem is further compounded with a larger deviation in ATCO standards being envisaged. There is therefore an urgent need to develop new methodologies to study the visual monitoring behaviour of ATCOs in their tactical control activity under different air traffic complexities, which will be present in the foreseeable future.

1.2. Motivation

In the tactical control activity of ATCOs, they are required to monitor the air traffic as they fly across their sector of jurisdiction using the radar display. This is performed by an ATCO, where they would monitor the radar display using their eyes for the various flights and path movements at various speeds and altitudes, which are constantly changing, as illustrated in Figure 1.1.

Figure 1.1. Illustration of ATCO monitoring the radar display. Source: RATCAS

Current approaches to address issues related to an ATCO's tactical monitoring activity both operationally and in training, remain limited, due to the lack of knowledge extraction and representation of this activity. Such is seen in three different aspects, which are namely the lack of exploitation of shared information between these physical heterogeneous data capture systems with human operated functions, as most of these mainly involved closed systems for one aspect of such human operated functions (system or human); the inadequate representation of tactical air traffic complexity; and the shortage of methods in extracting and representing an ATCO's monitoring behaviour of the air traffic situation.

Firstly, the issue of the lack of exploitation of shared information between human and system operated functions will be discussed. In ATC, system operated functions include alerts like the STCA and the new Tactical Separation Assured Flight Environment (T-SAFE) [22], which were developed in an attempt to highlight to ATCOs, to act on two conflicting aircraft when there is a loss of separation between them and a collision is due to occur in 90 to 120 seconds. Such is being achieved by flashing out the track and label of the two conflicting aircraft on the radar screen in red colour, when a collision is scheduled to happen. On the other hand, for human operated functions, subjective and objective approaches were used. Subjective methods normally come in form of questionnaires and rating scales of ATCO, which are dependent on the ratings from the Subject Matter Experts (SMEs) and the

response of the ATCO's perception of a scenario [23, 24]. For objective approaches, they include the use of recorded data analysis, simulation replays or operational ATCO data to derive assessment metrics and objective measurements like number of landings, the amount of time spent in the sector and many more [25]. Furthermore, physiological methods like eyeball movement, brainwaves, heart rate, other form of objective methods, are also used.

Although such singular operated functions can extract knowledge on the tactical control activity of ATCOs, such knowledge is not comprehensive as it does not cover the other aspect of this activity. For ATC applications which involve dynamic data covering both aspects, the solution needs to be synchronous and of a high resolution, to enable a clearer understanding of the situation. Present solutions involving both the human and system aspects in ATC are limited in the degree of resolution in both time and space, together with the level of synchronisation. Hence, these solutions are not suitable to extract knowledge during an ATCO's tactical monitoring activity.

In terms of tactical air traffic complexity, the increasing amount of dynamic air traffic flow of greater traffic complexity would greatly affect ATCOs' tactical monitoring tasks. These changes will no doubt impact their operational performance and taskload in terms of tactical radar monitoring, guiding of dynamic aircraft movements while maintaining high operational safety standards [9, 26]. To better understand tactical air traffic complexity, researchers have explored various methods such as the study of the aircraft's air route and its conflict characteristics [27-30], and in the strategic time domain, by studying the air traffic flow patterns via optimisation, mathematical models and network theories in different phases of flight [31-35]. Air traffic complexity is then quantified through methods like the modelling of air traffic flow and analysis of the air transportation network mathematically, so as to better aid ATCOs, in their tactical monitoring and controlling tasks, by allowing them to adopt appropriate tactical control strategies based on the traffic flow and network characteristics. However, such methods are unable to quantify the air traffic complexity tactically, as they are handling complexity in the planning and strategic time domain in ATC, thereby resulting in its inadequate representation of tactical air traffic complexity.

For the monitoring behaviour of ATCOs, the Federal Aviation Administration (FAA) listed six main causal factors influencing operational errors (OE) of ATCOs, which are namely data posting, radar display, communication error, coordination error, position relief briefing and aircraft observation. Except for aircraft observation, the remaining five aspects are associated with radar operations [36]. Pounds et. al investigated on the distribution of the OEs, which stands at Data Posting (9.8%), Radar Display (58.7%), Aircraft Observation (Towers Only, 1.5%), Communication Error (25.6%), Coordination (4.5%), and Position Relief Briefing (0%) [37]. It is also found that the majority of these factors are associated with radar operations, where misidentification and inappropriate use of displayed data were found to be the key contributing factors [38].

Further research on radar operations revealed that 95% of human induced OEs are owing to skill-based errors (a result of habitual actions associated with individual's attention, memory and/or technique execution) [38-41], while the most significant cognitive error involves perception and vigilance in planning and radar monitoring tasks [37, 42-45]. Most of these relate to perception and vigilance errors such as no visual detection, late visual detection and forgetting previous actions. Thus, efforts to reduce OEs should be focused on an ATCO's perception and vigilance, in monitoring of radar display. Analysis also showed that OEs occurred more often during the en-route portion than the terminal manoeuvre area [46, 47]. Similarly, using Endsley's Situation Awareness (SA) model [19], perception (Level 1 SA) and comprehension (Level 2 SA) when combined constitute 88% of SA errors [48], which consists of errors like the failure to monitor or observe data and difficulty to detect and perceive data [49]. Hence, the ability to perceive the status, attributes, and dynamics of relevant elements in the environment is essential for the comprehension of the current situation thereby enabling one to project and make appropriate decisions of future situations [50]. Such findings remain relevant till today.

Some examples of these errors obtained from SKYBRARY, Eurocontrol Accident and Incident Database, with the full details of these cases found in Appendix A, include the following:

- Over-focusing on other regions of the radar display, resulting in the Short-Term Conflict Alert (STCA), not being able to break the mental picture that the controller had of the situation of the sector, as seen in the incident involving a AT72 (Golden Air) / JS32 (AIS Airlines) in the en-route airspace, north east of Jonkoping Sweden in 2012.
- Misjudgement of separation standard due to air route design, resulting in a loss of separation between two A332 aircraft operated by Qantas in the en-route airspace, near Adelaide South Australia in 2013.
- Performance degradation due to the fatigue of ATCO, resulting in a late recognition of conflict and insufficient time in resolving, which occurred between two aircraft near the vicinity of Toronto City Airport, Canada in 2010.
- Wrong judgment of trainee ability during On Job Training (OJT) by the OJT Instructor (OJTI), as the OJTI was unable to judge that the trainee was overwhelmed by the challenging traffic situation, resulting in a potential conflict and intervention by the OJTI, involving an A318 (Air France, AFR 989Z) and B738 (Ryanair, RYR 1702) under the en-route sector in Trasadingen Switzerland in 2009.

As a result, problems like ATCOs facing difficulties in responding and resolving the conflict situation due to increasing traffic complexity, losing their awareness via over-focusing on particular spots, unawareness or failing to observe the appropriate flight parameters or data on the radar display still persists. This challenge is further compounded owing to performance degradation, fatigue and variation amongst ATCOs in an increasingly foreseeable congested airspace. Therefore, it is crucial to extract and represent how an ATCO perceive and comprehend the different radar elements on the radar screen, to maintain their awareness of where the aircraft are on the radar screen [10]. Such is even more critical in future, as tactical complexity is increasing and ATCOs shift towards a more active monitoring role.

To recap, there is therefore a need to extract and represent knowledge of an ATCO's tactical activity in three different aspects, by using both human and system operated functions, so that information on the ATCO's tactical monitoring activity is presented accurately. In doing so, the tactical monitoring activity can be better captured and

understood, tactical air traffic complexity be better represented and the perception and comprehension of ATCO be depicted more accurately, to aid ATCOs and prevent such problems in future.

1.3. Objective

The objective of this research is to develop an eye-hand movement model for traffic complexity evaluation and monitoring enhancement for ATCOs. This eye-hand movement model seeks to integrate information from both dynamic radar and human data streams in real time, while being synchronous. To do so, novel methods are developed to better extract and represent knowledge of an ATCO in their tactical monitoring activity, under radar surveillance in area control. To achieve this goal, efforts can be devoted to addressing the three aspects of an ATCO's tactical monitoring behaviour, comprising of the exploitation of shared information between human and system operated functions, the depiction of tactical air traffic complexity and the determination of an ATCO's perception and comprehension level, where there is a lack of knowledge in what types of data are to be extracted and how they represented adequately. These have paved the way for the following sub-objectives to be studied:

- Development of an innovative measurement for the tactical monitoring activity of ATCOs, through the establishment of a data activity register frame where image and textual information depicting ATC surveillance activities at a specified spatial and time reference. Such allows for new knowledge extraction and representation in ATC. Using a real time eye tracking system, exploit and analyse an ATCO's monitoring behaviour by integrating the two sets of activity data (air traffic flight movements and eye tracking metrics) in a highly dynamic changing and synchronous manner in real-time with respect to both spatial and time frames.
- Calculation of tactical air traffic complexity using a novel method that is more reflective of what an ATCO encounters in the tactical monitoring tasks, to better represent the different tactical complexity present. Using this tactical complexity method, investigate the complexity time profile of aircraft pairings under different traffic flow configurations.

- Creation of innovative eye signatures to capture and evaluate the perception and comprehension level of ATCOs, by combining both eyeball and hand movement on the ATC interface. Individual signatures can be created for three key ATCO's tactical monitoring behaviour (generic flight path monitoring, switching of aircraft frequency and potential conflict situation). Investigate ATCO expertise level through these eye signatures as well as the different flight characteristics for each tactical monitoring behaviour.

1.4. **Organisation of Thesis and Research Framework**

The thesis is organized into seven main chapters. Following the introduction chapter, Chapter 2 reviews the state-of-the-art techniques used in the three sub-objective areas, which are knowledge extraction and representation of an ATCO tactical monitoring activity using eye tracking techniques, air traffic complexity measurements and approaches to capture and evaluate how ATCO perceive and comprehend radar elements on their radar display. The reviewed techniques are being evaluated and solutions to overcome the limitations are proposed. An outline of the research framework, highlighting the several contributions of this thesis is shown in Figure 1.2.

Chapter 3 presents the development of the innovative interaction interface, for extracting new knowledge of an ATCO tactical monitoring activity, using real time eye tracking system. ATC application (air traffic flight movements and eye tracking metrics) is used to illustrate this real time eye tracking system. It is based on a “Dynamic Data Alignment and Timestamp Synchronisation Model”, which matches the timestamps of the two data streams, by aligning them to the same spatial reference frame before fusing them together into a data activity register frame. A deeper illustration of this new knowledge, in the form of newly derived metrics, are also showcased in this chapter.

Chapter 4 illustrates the calculation of tactical air complexity using a novel method, called the Conflict Activity Level (CAL), to reflect the instantaneous tactical air traffic complexity on the radar screen. Furthermore, a novel complexity time profile model, CAL Separation Axes Theorem (CAL-SAT) is developed, to determine the complexity time profile between aircraft pairs in different flight configuration. Hence,

the quantification of tactical air traffic complexity instantaneously and across time is performed in this chapter.

Figure 1.2. Research Framework

Chapter 5 explains the creation of innovative eye signatures to capture and evaluate how ATCO perceive and comprehend elements on the radar screen. Signatures were created for three different key aspects of ATCO's tactical monitoring activity, generic flight path monitoring, switching of aircraft frequency and potential conflict situation, using a combination of eyeball and hand movement on the ATC interface. A comparison of the difference in the perception and comprehension levels is also conducted for ATCOs of different expertise levels.

Chapter 6 showcases the use of the proposed eye-hand movement model of an ATCO tactical monitoring activity, for traffic complexity evaluation and monitoring enhancement. Using a few selected instances, the integration of both traffic complexity and monitoring performance from both dynamic radar and human data streams in real time, while being synchronous, is showcased.

Chapter 7 provides a conclusion of the accomplished work in this thesis and highlights the major contributions of this research, while providing suggests for future work.

2. Chapter 2 Literature Review

This chapter reviews the state-of-the-art methods in extracting and representing knowledge across the different aspect of an ATCO's tactical monitoring activity. It first begins with a comprehensive review of the state-of-the-art eye tracking systems for knowledge extraction and representation of an operator's monitoring activity for electronic surveillance systems. Subsequently, the review will discuss the various state-of-the-art air traffic complexity approaches used and their applicability in calculating and quantifying tactical air traffic complexity. Lastly, techniques that attempted to capture and evaluate the perception and comprehension of ATCOs are also discussed and reviewed.

2.1. Review of Eye Tracking System for Knowledge Extraction and Representation of monitoring activity

To better extract and represent the operator's monitoring activity on a dynamic display, eye tracking techniques should be the main mode of measurement and the system should account for both eye and dynamic display data. Eye tracking technique is used as it is viewed to be the most direct form of measurement of an operator's visual monitoring behaviour [51]. Figure 2.1 shows the different types of eye tracker being used, ranging from wearable ones to remote eye trackers, which have been deployed in many different fields.

Figure 2.1. Eye Trackers Types (a) Wearable Eye Tracker (b) Remote Eye Tracker, positioned at the bottom of screen

In addition, this eye tracking system should also be able to pinpoint when is the operator looking at a particular object, to allow for a deeper understanding of the

operator's monitoring activity. To do so, the eye movement and dynamic display data needs to be fused by synchronising in time and aligning spatially, while considering the changes in dynamic data. Furthermore, to correctly identify the object that the operator is looking at, the eye tracker should offer a spatial resolution that is lesser than the size of the object and an update rate that is faster than that of the dynamic display. Using these criteria, real time eye tracking systems for the knowledge extraction and representation of an operator's monitoring activity are reviewed in this section.

Most researchers used real time eye tracking systems to evaluate how operators look at the whole display or at different regions, on static display images. Common synchronised activities range from usability studies in webpages and layouts, improvement on design workflow and performance, evaluation of cognitive strategies. In the evaluation of how participants looked at search engine results on webpage, Dumais et. al [52] used a remote eye tracker in a real time eye tracking system, which was first calibrated to view the layout of the static search engine result page at different display regions. Eye metric parameters such as their gaze duration and its corresponding heatmap were captured across the entire experimental duration, with fixations more than 100 milliseconds (ms), having a radius of 35 pixels. Different groups of participants were then asked to complete a search task in 2 to 3 minutes, by looking at various regions in the display. This information was then used to identify different user types in order to better design search interfaces for them. Goldberg et. al used a remote eye tracker in a real time eye tracking system to deduce the web based tasks of the participants [53, 54]. The different eye metrics were matched to the exact static objects, with a fixation radius of 10 pixels and a duration of more than 200 ms. Evaluation of the usability of the web interface was then performed by comparing these matched metrics across the different experimental duration of 20 minutes.

In work performance measurement, Acik et al [55], used a remote eye tracker to deduce the best surgical static interface design in which surgeons can perform their surgical tasks more efficiently, through a real time eye tracking system. Eye metrics like fixation duration, saccade amplitude and direction were computed using a

fixation radius of 42 pixels and a duration of more than 100ms, which were then used to record and evaluate two separate static interface designs with different layouts for a duration of 20 minutes. Ratwani and Trafton developed a real-time eye tracking system, using a remote eye tracker, for analysing the performance of operators, so as to predict and prevent post-completion errors [56]. Fixations derived from this real time system has a 15 pixel radius, a duration of more than 250ms. Static interface display content like the ordering of a sea-vessel production task and the entering a stock order in a financial management task was used as test cases, with each task taking 90 seconds. A logistic predictive model, which used the real time eye tracking data and display data, was used to process and deduce the human error, by matching eye data to specific objects on the display, across various time intervals. To aid the interaction between disabled people and machine interfaces, De Santis & Iacoviello developed a real-time eye tracking system to do so [57]. Tracking algorithms were developed to determine where exactly the participant looks at the display with a static content. Technical specifics for eye metrics, like fixation, were, however, not specified in this paper.

For cognitive strategy observations and evaluation, Taukari et. al [58], used a chin mounted eye tracker to compare the cognitive strategies of novice ATCOs [58]. Computed fixations are those with time spans of more than 250ms having an accuracy of 1 degree, which was evaluated to be having a 35 pixel radius over a fixed distance of 60 centimetres in front of a 2K screen. Eye metrics like pupil diameter, number of fixations and scan path length were evaluated across different static regions over a 10 seconds duration, on the radar screen, independent from its content. Comparisons can then be made across different times to highlight the differences between novice and expert ATCOs in resolving conflicts. Kang et. al used a real time eye tracking system, with a remote eye tracker to capture the ATCO's eye tracking data, before mapping it to a still radar image of 19 inch monitor to study the monitoring performance of ATCOs. Eye data have an accuracy radius of 34 pixels and runs at 60 Hz, while the experimental duration lasted for 5 minutes. Analysis of how ATCOs looked at the aircraft (an object on the display) was performed after the simulation, by studying which and how aircraft are scanned together with their pairing and grouping from the ATCO's eye ball movement [59, 60]. Further algorithms were then developed to

compute and classify the scanpath strategies of ATCOs, in order to characterise their visual scanning patterns [61, 62]. Their individual performance determined using the duration of scanning required before conflict detection was derived.

From these eye tracking applications, their works generally involve eye interrogations made at sizeable spatial regions on static display images in a synchronous manner where the captured eye metric data matched that of the objects on current display. Eye data like fixations offered a high spatial resolution from 15 to 42 pixels, of 100 to 250 ms in duration. When applied to ATC, this meant that these eye tracking systems can specify which flight object an ATCO was looking at in 250ms, as this flight object tends to be larger than its spatial resolution of 42 pixels. As a result, these real time eye tracking systems can uncover how participants looked at different objects on the display. However, as the monitoring performance was conducted on a static image, such eye tracking systems could not deduce how ATCOs looked at the moving flight object movement on the dynamic radar display. For these applications on static images, the eye and radar data was aligned to the same spatial reference throughout the experimental duration as there are no dynamic changes in the radar data both spatially and in time. Thus, participants were unable to interact with the radar screen by moving objects or adjusting the radar screen dynamically, via the zooming and panning of the radar screen at any instant of the experimental duration, as they will disrupt the alignment of the eye and radar data. Furthermore, any updates to the flight object position due to a radar update across time will not be considered. Therefore, analysis like the number of aircraft spotted by the ATCO flying across a fixed point on the radar display over a fixed duration and the number of aircraft label spotted by the ATCO while allowing him to re-position them on his own discretion cannot be performed.

On dynamic display data, research work on real time eye tracking systems are normally conducted in the field of ATC where positions of the flight objects are constantly changing with every radar update and ATCO interaction with the dynamic radar display. Marchitto et. al investigated how eye tracking metrics like saccade duration, peak velocity and frequency of fixations, are good indicators of ATCO's performance and workload, with a remote eye tracker [63]. Technical specifications

of the eye tracker were not mentioned in this paper. Evaluation of ATCO's performance and workload was conducted using only the eye tracking metrics, in 7 minute step intervals for the entire experimental duration of 1 hour, on the whole radar display. 7 minute step interval was chosen as it was the time taken for the aircraft to fly to the point of separation loss on the whole radar screen. In another study, Imants et. al used a real time eye tracking system with a remote eye tracker to evaluate the monitoring performance of ATCOs. Eye metrics captured were of 100ms, with a 0.5 degrees accuracy, which can be calculated to a radius of 18 pixels for a fixed distance of 60 centimetres in front of a 2K screen. Eye metrics computed consist of scanpath lengths, fixation duration, fixation clustering and the area of convex hull formed by fixation of where the ATCO is looking, together with its corresponding duration of the different ATC tasks like monitoring and planning over 5 minute step intervals of the experimental duration [64]. A 5 minute step interval was chosen as that is the time taken for one event instant in the scenario. Wang et. al also used a remote eye tracker in his real time eye tracking system to classify novice and expert ATCOs by applying Multifractal Detrended Fluctuation Analysis method to the time series data, of fixation duration and saccadic velocity [65]. This eye tracking system has a fixation radius of 70 pixels for a fixed distance of 60 centimetres in front of a 2K screen. A similar correlation is also used to study the effects between air traffic parameters and ATCO's eye movement in the different air traffic scenarios, in a specified static regions of 200 by 100 pixels on the radar screen [66].

From these real time eye tracking systems used on dynamic display data, the eye data and the radar data were not fused. Although the timestamps of the eye and radar data are synchronised to enable analysis in different step intervals with respect to radar scenarios, the eye data is not matched to the changing flight object spatially. Such is the case operationally since spatially, the flight object changes dynamically, as ATCOs can interact with the radar display dynamically by zooming and panning it, moving the aircraft label to any position on the radar display at his own discretion. Hence, any dynamic changes on the radar screen spatially are not accounted for in these reviewed eye tracking systems. As a result, instantaneous and duration based analysis of where and how ATCOs looked and behaved with respect to the changing flight object movement while allowing the ATCO to interact with the radar display

freely, could not be performed effectively in real time. Therefore, analysis like monitoring behaviour of how an ATCO look at the different flight objects across time, whether there is a late monitoring of aircraft by an ATCO could not be performed.

2.1.1. Evaluation of real time eye tracking systems for Knowledge Extraction and Representation of monitoring activity

To use real time eye tracking systems for applications that involve dynamic display data spatially and in time, it would require the following five features, to correctly fuse the eye movement and dynamic display data. Firstly, the timestamp of the eye and display data needs to be synchronised. Subsequently, this system should use dynamic display data while aligning both the eye and dynamic display data spatially. Changes in time from the dynamic display data should also be considered in the system, while taking into account a change in space of the dynamic display data. Hence, it is believed that by fulfilling the five desired features, the real time eye tracking system would aid in ensuring that a deeper understanding of an operator's monitoring activity, by identifying when the operator is looking at an object on the dynamic display.

The reviewed real time eye tracking systems is then measured against these desired features, as summarised in Table 2.1. This showcases their ability in fusing the eye movement and dynamic display data.

Table 2.1. Comparison of Real Time Eye Tracking Systems with the Desired Requirements

Real Time Eye Tracking Systems	Synchronised timestamp of Eye and Display Data	Uses Dynamic Display Data	Aligns Eye, Radar Data Spatially	Accounts for dynamic display data in time	Accounts for dynamic display data spatially
Dumais et. Al	✓	✗	✓	✗	✗
Goldberg et. Al	✓	✗	✓	✗	✗

Acik et al	✓	✗	✓	✗	✗
Ratwani and Trafton	✓	✗	✓	✗	✗
De Santis & Iacoviello	✓	✗	✓	✗	✗
Taukari et. Al	✓	✗	✓	✗	✗
Kang et. Al	✓	✗	✓	✗	✗
Marchitto et. Al	✓	✓	✗	✓	✗
Imants et. Al	✓	✓	✗	✓	✗
Wang et. Al	✓	✓	✗	✓	✗

From Table 2.1, it can be seen that the real time eye tracking systems applied only on static display data and are unable to be used for dynamic display data as they could not account for the dynamic display data changes both spatially and in time. For real time eye tracking systems applied on dynamic display data, the eye and display data are not aligned to the same spatial reference frame and any dynamic spatial display data changes are not accounted for. When this is applied to the field of ATCO to analyse their monitoring behaviour and performance, it requires a real time eye tracking system that is able to fuse dynamic radar display data while having an overall spatial resolution of less than the size of the flight object, and a time resolution less than the duration of radar update at the same time. Besides this, it aims to cater for

five desired requirements as listed in Table 2.1. Such requirements are also needed in other applications involving dynamic display data like vessel traffic monitoring, security surveillance and other forms of surveillance activities, while factoring the spatial and time resolution of the application of interest. Presently, the reviewed real time eye tracking systems are unable to meet these requirements when applied to a dynamic display data. Hence, there is a need to develop a new real time eye tracking system by employing a new innovative interaction interface to support this knowledge-intensive engineering task.

2.2. Review of Air Traffic Complexity Approaches

Different air traffic complexity approaches are reviewed in this section, as air traffic complexity represents a significant portion of an ATCO's monitoring activity on the radar screen. Air traffic complexity is multi-dimensional and is dependent on static sector characteristics and dynamic traffic patterns [67]. It is defined as "how difficult a given traffic situation is, based on the control activity required to resolve it and respond to an additional aircraft entering the airspace" [68]. For the tactical air traffic complexity of a given sector to be measured, aircraft's data, flight intent and characteristics should be captured and represented in a way to enable real time computation [19, 69, 70]. In addition, tactical air traffic complexity should cover a broad spectrum of air traffic situations and computed across time. Dynamic traffic flow and its network characteristics should also be considered [70]. Hence, to determine the level of air traffic complexity of a given sector, a review into several commonly used methods to validate air traffic complexity will be discussed in this section.

A very well-known complexity metric approach is Dynamic Density (DD) developed by Laudeman et al., the National Aeronautical and Space Agency (NASA) [71]. The DD approach consisted of eight traffic complexity terms such as number of heading changes, number of speed changes, number of altitude changes, number of aircraft with a Three-Dimensional (3D) Euclidean distance of 0 to 5 and 0 to 25 nautical miles, the number of conflicts predicted in 0-25, 25-40 and 40-70 nautical miles. Others like Kopardekar and Magyarits, Kopardekar et al., Sridhar et al. and Masalonis et al. have refined the approach to include proximity measurements, conflict state and time

horizon, while Masalonis et al. have also included aircraft's intent and only used metrics that represent an aircraft's characteristics [70, 72-75]. These approaches aimed to better help strategic planners to make better traffic flow management decisions while minimising airspace overload. Nevertheless, such complexity models do not account for individual flight orientation and location. Although DD and its variants can provide some degree of robust evaluation of the airspace complexity at hand, these approaches rely mainly on historical rather than real-time data. Computation of complexity level for tactical use both instantaneously and across a duration would therefore not be appropriate. Besides, for tactical radar control, ATCOs would need to look at the radar display and display information with reference to the orientation and locations to the origin to perform their tasks. Such information is not captured via these approaches.

Another commonly used model by Chatterji and Sridhar seeks to measure air traffic complexity using a set of 16 terms, which are descriptors of traffic pattern based on its second order statistical measures of the positions and velocities of the aircraft [76]. These measures include traffic volume, aircraft separation between pairs, distribution of aircraft pattern, speed and mix, closing rate of one aircraft with respect to another aircraft and conflict level of resolution. Temporal proximity conflict calculation between aircraft was performed pairwise by taking into consideration the vertical and lateral separations. This complexity metric seeks to use a precise pairwise calculation to determine the conflict characteristics of an aircraft, discounting manoeuvres with no effect on complexity. This complexity model is, however, limited to individual evaluation of an aircraft pair and does not capture the aircraft's intent among various aircraft operating within that region.

In the approach of Boag et al., relative terms between aircraft parameters were used to compute its relational complexity [77]. Variables such as relative flight level, relative speed and relative trajectory are used to compute the relational complexity. Their complexity metric focused on the temporal sequence of separation standards, by assigning a relational complexity value to the time that the aircraft pairs lose separation. Four variables relating to the time when the aircraft pairing enters and leaves conflict, lateral and vertical conflict types were used to determine five levels

of relational complexity. Such a complexity computation is purely based on the timing that an aircraft pairing enters and leaves the conflict. In Radanovic et al., a concurrence events identification complexity model was used to identify and assess impending conflict situations [78]. This model used the projection of an aircraft's 4D trajectory to compute the traffic complexity in a tactical situation. An intent-based conflict detection algorithm was first applied to determine the conflict probability from the 4D trajectory of aircraft pairings at the 3D point in a designated airspace. A cluster of aircraft can be evaluated by extending the envelope boundary with respect to the 3D point. Complexity was computed using the aircraft count and evolving 4D geometries within this extended cluster. These models suffer from prediction inaccuracy when impending conflicts have been resolved beforehand, as complexities are only computed in conflict scenarios. It must be said that both relational and concurrence events identification complexity models were not able to evaluate varying traffic patterns and situations both instantaneous and across a duration.

In Delahaye and Puechmorel and Puechmorel and Delahaye dynamic system theory coupled with Kolmogorov-Entropy was used to compute traffic complexity [79, 80]. This was done by quantifying the level of disorder in the aircraft's trajectory within a designated airspace. Relative displacement and velocities between aircraft pairs were used to compute a density function, a convergence and divergence function together with a sensitivity function. Kolmogorov-Entropy was then used to calculate the intrinsic complexity for a designated airspace topology. A final complexity indicator, deduced based on four derived functions, seeks to provide the situation complexity by taking into account the aircraft's current position and velocity, as well as a broad spectrum of traffic patterns and situations. The approach used instantaneous values of aircraft characteristics thereby making it suitable for computing tactical traffic complexity. However, it was not able to pinpoint exactly where the key conflict lies, as the final complexity score is of a higher order term derived from the sum of relative displacement and velocities of all aircraft pairs.

2.2.1. Evaluation of Air Traffic Complexity Approaches

In order to establish a suitable complexity indicator to compute tactical complexity to aid an ATCO in the operation of their tasks, the approach should have the following desirable features. This includes the ability to perform instantaneous aircraft data

capture for real-time computation to facilitate tactical monitoring, projection of an aircraft's flight intent [19, 69, 70], capability to evaluate a broad spectrum of air traffic situations, dynamic and meaningful representation of changes to aircraft characteristics [70], determination of various complexity scores at different regions on the radar screen to enhance tactical monitoring performance [59, 81] and compute complexity change across time. Furthermore, it should also be able to consider the dynamic air traffic flow and its network characteristics in real-time so that tactical measures can be taken by ATCOs, while being able to project complexity ahead, in terms of time, thereby allowing tactical measures to be taken appropriately beforehand. An illustration of the traffic complexity, from the traffic variables, is illustrated using an aircraft (GIA274) in Figure 2.2. Hence, it is believed that by fulfilling the seven desired features, tactical air traffic complexity can be computed and such would facilitate greater awareness among ATCOs in terms of task prioritisation and adoption of appropriate tactical control strategies based on the different complexity levels.

Table 2.2 compares the various reviewed approaches against a set of six desirable features used to determine traffic complexity. From Table 2.2, Chatterji's pairwise comparison, Boag's Relational Complexity and Delahaye's dynamic system and entropy modelling best satisfies the set of desired features for the traffic complexity model, with DD and its variants satisfying the least.

Figure 2.2. Illustration of traffic variables influencing complexity using a portion of the radar screen

Table 2.2. Feature comparison of existing complexity indicators adopted

Features	Dynamic Density (DD) and its variants ^a	Masalonis's Model ^b	Chatterji's pairwise comparison ^c	Boag's Relational Complexity ^d	Radanovic's model ^e	Delahaye's dynamic system and entropy modelling ^f
Instant aircraft data capture ¹	✗	✓	✓	✓	✓	✓
Uses aircraft's intent ²	✗	✓	✗	✓	✓	✓
Coverage of broad air traffic situation spectrum ³	✓	✓	✓	✗	✗	✓
Properly represent an aircraft's characteristics ⁴	✗	✗	✓	✓	✓	✓
Targeted Score for regions of radar screen ⁵	✗	✗	✓	✓	✗	✗
Provision to compute complexity across time ⁶	✓	✓	✓	✓	✓	✓
Considers dynamic air traffic flow and network characteristics in real-time ⁷	✗	✗	✗	✗	✓	✓

¹Instantaneous aircraft data capture is necessary for real time computation of complexity for tactical ATC.

²Aircraft's intent is required as ATCOs project them for their tactical monitoring tasks.

³Coverage of broad air traffic situation is necessary as it is dynamic and varies across time.

⁴Proper representation of an aircraft's characteristics is necessary so that any complexity computation is reflective of air traffic complexity in tactical monitoring. This includes an individual flight's space and time information, location and orientation with respect to the radar screen, while discounting irrelevant parameters.

⁵A targeted, detailed complexity is required on different regions of the radar screen, as ATCOs tend to monitor the radar screen in different regions and zones.

⁶Complexity should be able to be computed across time, in order to study the changes in complexity level of tactical ATC at different time instances.

⁷Complexity should be able to account for dynamic air traffic flow and network characteristics, so that the time projection takes these factors into consideration.

^a Laudeman et al. (1998), Kopardekar and Magyarits (2002; 2003), Kopardekar et al. (2009), Sridhar et al. (1998)

^b Masalonis et al. (2003)

^c Chatterji et al. (2001)

^d Boag et al. (2006)

^e Radanovic et al. (2017)

^f Delahaye and Puechmorel (2000), Puechmorel and Delahaye (2009)

2.3. Review of Approaches for Capturing and Evaluating ATCO Perception and Comprehension

This section reviews the different state-of-the-art approaches for capturing and evaluating an ATCO's perception and comprehension level. To do so, the most direct form of measurement has to be used, to describe the different monitoring activities. This is so that any changes can be detected and identified accurately. In addition, these measurements to capture and evaluate how an ATCO's perceive and comprehend elements on the radar display, would need to be consistent and not subjected to any form of bias, and should not be disrupting their primary workflow. Furthermore, these measurements should be evident among participants of all expertise levels and can also be used as a measure to differentiate them. As perception and comprehension provide some measures of a person's Situational Awareness (SA), this section will also discuss the literature of SA methods that seeks to capture and evaluate an ATCO's perception and comprehension level.

2.3.1. Subjective Methods

Subjective assessment is a commonly used approach to determine an ATCO's SA, which composes of their perception and comprehension level. They are normally in the form of self-rating by the ATCO, or assessor rating scored by Subject Matter Experts (SMEs).

Situational Awareness Rating Technique (SART), is an example of a self-rating method [82]. SART is a multi-dimensional, self-rating technique aimed at measuring the overall SA by rating ATCOs on demand on attentional resources, supply of attentional resources and level of understanding [82]. It is conducted at the end of every exercise where subjects are to rate their understanding of the situation based on the tasks performed, using a seven-point Likert scale (1 = Low, 7 = High) in order to gain a subjective measure of operator SA, on ten dimensions. The ten dimensions of measurement are, familiarity of the situation, focussing of attention, information quantity, information quality, instability of the situation, concentration of attention, complexity of the situation, variability of the situation, arousal, and spare mental capacity. SA is then calculated using the formula, $SA = \text{Understanding} - (\text{Demand} - \text{Supply})$ [82]. The Situation Awareness Rating Scales (SARS) technique is another subjective rating technique, developed for the military aviation domain [83]. When

using the SARS technique, participants subjectively rate their performance on a six-point rating scale (from acceptable to outstanding) for 31 facets of fighter pilot SA. The SARS SA categories and associated behaviours were developed from interviews with experienced F-15 pilots [83]. For SA measurement via assessor rating by SMEs, Behaviourally-Anchored Rating Scales (BARS) is one such example. In BARS, SMEs include specifics on what is to be rated, containing intermediate and end points that are tied to observable behaviours. BARS has been used by researchers for ATCO selection and training, where a high correlation is found between peer and supervisor ratings [84].

Subjective SA measurements are usually assessed quickly through specific queries and quantifiable results after the experiment, thereby not disrupting the natural flow of tasks. These measurements only seek to provide an assessment of an ATCO's SA, while not capturing and evaluating their perception and comprehension levels directly. Furthermore, as these methods are only conducted after the experiment, changes in the perception and comprehension of ATCO across the entire experimental duration would not be detected. As a result, an in-depth understanding of changes in an ATCO's perception and comprehension level would not be possible, and this is further supported by the fact that people are poor at reporting detailed information about past events and participants tend to not recall periods of tasks when they possess low SA [85]. In addition, such subjective methods are also dependent on the interpretation of the ATCO or assessor, subjecting it to various forms of biasness. Therefore, such subjective measurements may not be suitable in measuring if the ATCO has perceived and comprehended the different elements on the radar screen accurately.

2.3.2. Objective Methods

Objective measures were also used to determine an ATCO's SA, by evaluating one's perception and comprehension level. These measures are not subjected to how individuals perceive SA and they are namely, response time, a set of derived assessment metrics and many more [86].

Situational Awareness Global Assessment Technique (SAGAT) is a well-established objective SA measurement, where ATCO are queried about their perception of the

situation by pausing the simulation at random timings [87]. Queries can be raised at more frequent intervals and the questions asked relate to specific data reflecting the three levels of SA [88]. Responses were then marked as correct or incorrect accordingly. Many research studies performed using SAGAT reported a high validity and reliability of it as an SA assessment technique, for applications ranging from fighter pilots to nuclear power plants [19] [89]. Another objective method is the Situation Present Assessment Method (SPAM) [90], which is a real-time probe technique developed to assess ATCOs' SA. Real time probes by the SMEs are deployed to evaluate the SA of ATCO and queries asked are based on information in the environment via telephone. The query response time for correct responses is taken as an indicator of the ATCO's SA. SA for SHAPE (SASHA) is another popular objective SA measurement which comes in two forms, online queries and post-exercise questionnaire [91]. The SASHA on-Line (SASHA_L) requires an SME to pose queries in real time based on what he views on the ATCO's screen. Such questions are generic in nature and formulated depending on how the scenario unfolds. Subjects are rated based on the accuracy of their answer and the time taken to respond. For SASHA questionnaire (SASHA_Q), it is designed based on well-recognised human factors principles and test participants are required to complete the questionnaire at the end of the simulation. Hence, for the SASHA technique, a detailed assessment of subject in real time is possible and it also has the advantage of both online assessment and post questionnaire to capture the SA in various forms.

Since such objective measures are not subjected to the interpretation of SMEs, assessors or ATCO, they are not subjected to the same amount of biasness as opposed to subjective approaches, thus making it more reliable [24]. However, they are not direct measurements of how an ATCO perceive the radar elements and comprehend them. Methods like SAGAT, SPAM and SASHA_L use real time probing technique to assess the SA of ATCOs. These techniques managed to evaluate the perception and comprehension level of an ATCO, as a correct response to a query indicates a good level of them. However, they are unable to explain the causes for changes in the perception and comprehension levels for the participants, as the responses are a result of how ATCOs perceive and comprehend information on the radar screen. In addition, such techniques have a high level of sensitivity, as they can detect changes in SA

throughout the experimental duration as the participants are queried more frequently, as opposed to post-experimental analysis [85]. However, by probing during the experimental session, it disrupts the participant's natural flow of tasks. Furthermore, such queries could possibly direct the attention of ATCO's to the required elements, causing biasness in return, making it less reliable. For SASHA_Q, it lacks sensitivity to detect changes in perception and comprehension levels throughout the experiment, as it is only conducted upon completion of experiment. Moreover, there is no disruption in the natural flow task.

2.3.3. Physiological Methods

Physiological measurement is a popular method used to measure and assess the SA. Physiological measurement can be traced easily across time, as it has the ability to capture the changes in bio-signals continuously [92]. This allows the evolution of how well an ATCO is able to perceive and comprehend to be studied, while causing minimal disruption to their tasks [9], as well as enabling physiological measurements, which are highly sensitive to such changes over the entire experimental duration, to be made. These methods of measurement fare better, as physiological signals are continuous in nature and are sensitive to changes in the ATCO's perception and comprehension, making it more suitable for its implementation in real time, as a monitoring aid. The physiological measurement that is most appropriate for this study, eye tracking technique, applied in ATC, will be reviewed in this section.

2.3.3.1. Eye Tracking Techniques

Eye tracking techniques, a type of physiological method, have been deployed increasingly in recent years by various researchers to study the visual monitoring behaviour of ATCOs. Its relevance, as highlighted by Lundberg and others [51], is the most direct form of measurement of the ATCOs visual monitoring behaviour.

Eye tracking studies can be conducted using a wearable eye tracker. Research conducted using wearable eye trackers in ATC are normally for understanding an ATCO's attention allocation on the new tool (automated conflict probe) which is introduced in their working environment. Rovira et. al used it to determine an ATCO's attention allocation of a new tool in the ATC area control environment, whereby the number of fixations on the radar display upon introduction of the

automated conflict probe is examined [93]. It is found that ATCOs spent more time looking at the radar display whenever there is imperfect automation, thus indicating that the ATCO is not aware of the new tool during instances of imperfect automation. Moehlenbrink used a head mounted eye tracking system to examine how the visual attention of tower controllers is affected, in a multiple remote tower setting, to determine best arrangement [94]. The ATCO's SA can thus be evaluated by understanding where ATCOs tend to look and how best to arrange their working position.

In these studies, wearable eye trackers are used to determine if a new tool is being looked at and utilised effectively by the ATCO. Consistent eye tracking results were generated, thereby showing its reliability as they are not subjected to biasness. In addition, these eye tracking signals can also be measured continuously throughout the entire experimental duration, making it sensitive to changes in how an ATCO looks at the new tool. This illustrates the ability of the eye tracking technique in capturing an ATCO's perception level. However, they are unable to illustrate and depict how this new tool is being looked at and utilised effectively, thus showing that an ATCO's comprehension level cannot be evaluated directly using wearable eye trackers. Furthermore, the use of wearable eye trackers and eye trackers with chin rest are obtrusive and causes discomfort to the ATCO's way of work, even restricting their head movement. Such discomfort could possibly affect the way ATCOs work, interfering with the primary tasks, creating some form of intrusiveness.

Remote eye tracker is also used to assess the visual monitoring behaviour of ATCOs. Kang et. al used scanpaths to determine the visual scanning of an ATCO's eyes on a radar screen from a remote eye tracker. A Maximum Transition-based Agglomerative Hierarchical Clustering (MTAHC) algorithm is then derived, to capture and evaluate the visual monitoring behaviour of ATCOs in conflict detection tasks, by understanding if the participants managed to detect and correctly identify a conflicting aircraft pair. Furthermore, ATCOs can then be classified according to their expertise level through this visual monitoring behaviour [59-61, 95]. Marchitto et. al then used saccade duration, peak velocity and frequency of fixations to assess the visual monitoring behaviour of ATCO on the radar screen for conflict detection

tasks, only in crossing situations [63]. A simple one crossing configuration involving two aircraft encountering a single conflict in the entire airspace, with angles variations at 30°, 60°, 90° and 120° were studied. Results using fixations and saccades highlighted that an ATCO's monitoring behaviour is influenced by geometry. Wang et. al also used a remote eye tracker to assess the visual monitoring behaviour of ATCO using radar surveillance. A Multifractal Detrended Fluctuation Analysis (MDFA) method was applied on the time series data of fixation and saccades to show that working experience have effects and a correlation on eyeball movement of ATCOs [65]. A similar correlation is also used to study the effects between air traffic parameters and ATCO's eye movement [66]. It is found that an experienced ATCO tends to fixate more on regions on the radar screen and fixation duration and saccadic velocity are crucial indicators to examine the expertise level of an ATCO.

These measurements of an ATCO's visual monitoring behaviour performed using remote eye trackers are shown to be useful in determining the perception level of ATCO, as they can capture where the ATCO is looking at on the radar screen in a non-intrusive manner, not disrupting the primary task of ATCO. In addition, they are also able to track the changes in the perception of an ATCO continuously across time. These results are also reliable as these studies have produced consistent results with similar trends and findings observed. However, such approaches are limited, as the measurements used, and algorithms developed are only applicable to specific situations of the ATC spectrum. Furthermore, they are insufficient in evaluating how the ATCO is looking at on the radar screen and their level of comprehension of the air traffic situation, as the measurements used usually depict if they are looking at certain elements and regions of the radar screen, with narrow understanding in the changes of how an ATCO looks and behaves. Subsequently, these output measurements are also limited in the ability to explain the changes in the perception and comprehension of ATCOs, as they are unable to correlate to the different elements of the radar screen for contextualising the air traffic situation deeper.

2.3.4. Evaluation of Techniques

To capture and evaluate the visual perception of humans, eye tracking was found to be an objective and direct technique which was used since the 1960s to understand

the visual perception of humans [96]. Many studies had employed eye tracking to determine attention and visual perception in applications such as reading [97], visual search [98] and image understanding [99], as it is able to pinpoint where the human is looking at. Therefore, it is essential to adopt the eye tracking technique to capture and evaluate the perception and comprehension of ATCOs.

Researchers have also stated the importance of several criteria to measure SA effectively, which are namely measuring only SA and no other factors, being able to accurately detect and identify changes in SA and not altering SA during the measurement procedure [85]. Furthermore, other researchers indicated that an effective SA measurement would require the same degree of repeatability of the data when measured under the same conditions over several attempts [100]. Similarly, with perception and comprehension being components of SA, their measurements would need to be consistent and not subjected to any form of bias, accurately detect and identify changes in how an ATCO perceived and comprehended elements on the radar display, while not disrupting them in order to capture and evaluate an ATCO's perception and comprehension effectively.

Additionally, in the tactical monitoring task of ATCO using radar surveillance, an ATCO is required to have a good perception of the different elements on the radar screen, comprehension of the traffic picture before executing the necessary actions timely. A good measurement of an ATCO's perception and comprehension should also be applicable across the full ATC spectrum, non-intrusive so that there will be no discomfort felt by the ATCOs, while measuring continuously across time. Hence, it is believed that by fulfilling these seven desired features, the monitoring activities among ATCOs can be captured and evaluated. Differences in monitoring behaviour between expertise levels can also be observed, which could allow new operational standards and training methods to be developed.

Using these seven desired criteria, the reviewed measurements for SA and perception, comprehension are being evaluated and shown in Table 2.3.

Table 2.3. Evaluation of SA Measurements

SA Measurements	Employs Eye Tracking Technique	Consistent, not subjects to bias	Accurately detect and identify changes	Non-disruptive	Across Full ATC Spectrum	Non-intrusive	Continuous across time
SART	✗	✗	✗	✓	✗	✓	✗
SARS	✗	✗	✗	✓	✗	✓	✗
BARS	✗	✗	✗	✓	✗	✓	✗
SAGAT	✗	✗	✗	✗	✓	✓	✗
SPAM	✗	✗	✗	✗	✓	✓	✗
SASHA_L	✗	✗	✗	✗	✓	✓	✗
SASHA_Q	✗	✗	✗	✓	✗	✓	✗
Wearable Eye Tracking Techniques	✓	✓	✗	✓	✗	✗	✓
Marchitto et. al	✓	✓	✗	✓	✗	✓	✓
MTAHC by Kang et. al	✓	✓	✗	✓	✗	✓	✓
MDFA by Wang et. al	✓	✓	✗	✓	✗	✓	✓

From Table 2.3, it can be seen that all the measurement techniques using remote eye trackers, Marchitto et. al, MTAHC and MDFA cater to 5 out of the 7 desired criteria. All these techniques lacked the ability to accurately detect and identify changes on how an ATCO is looking and behaving throughout the tactical monitoring activity,

across the full ATC spectrum. These are important features, as it allows the desired measurements to be sensitive and accurate in detecting changes on how the ATCOs monitor for a wide variety of cases, while fulfilling the other requirements of being consistent, non-disruptive, non-intrusive and continuous across time, so that ATCOs can still work comfortably in their natural environment. As a result, this evaluation showed that there is a need to develop a new, real time measurement to capture and evaluate an ATCO's perception and comprehension level in their tactical monitoring task under radar surveillance, that fulfils all seven of the listed criteria.

2.4. Summary of Review

A review of the state-of-the-art techniques in addressing the three key challenges faced in the extracting and representing knowledge of an ATCO tactical monitoring behaviour is summarised.

For the challenge of the lack of exploitation of shared information between human and systems operated functions in ATC, it is found that few systems deployed a combination of both human and systems operated functions. Among those systems applied on dynamic display data involving real time eye tracking techniques (an essential tool for capturing ATCO monitoring behaviour), they are unable to account for these changes both spatially and in time at the same time. Therefore, it is necessary to develop a new method, as part of a real time eye tracking system to account for these dynamic data changes spatially and in time. To do so, this real time eye tracking system needs to fuse dynamic radar display data while having an overall spatial resolution of less than the size of the flight object, and a time resolution less than the duration of radar update at the same time.

Subsequently, a state-of-the-art review on the issue of inaccurate depiction of tactical air traffic complexity revealed that most air traffic complexity calculation methods are more catered in the strategic time domain and not tactically. For methods that depict tactical air traffic complexity most accurately, they are lacking in the consideration of an aircraft's intent, the dynamic air traffic flow and network characteristics, while not being able to provide a localised complexity score and not covering a broad air traffic flow spectrum at the same time. As a result, there is a need to develop new methods to better represent tactical air traffic complexity more

accurately. Such is achieved by performing instantaneous aircraft data capture for real-time computation, projecting an aircraft's flight intent, evaluating across a broad spectrum of air traffic situations, determining various complexity scores at different regions on the radar screen while computing complexity changes across time. Furthermore, this new method should also be able to consider the dynamic air traffic flow and its network characteristics in real-time, and be able to project complexity ahead, in terms of time, for tactical measures to be taken appropriately beforehand.

On the challenge of extracting and representing new knowledge to determine an ATCO's perception and comprehension level, a thorough review showcases the use of various approaches like subjective, objective and physiological methods by researchers. Of these approaches that were adopted by researchers, physiological methods, in particular eye tracking technique, is found to be the most objective and direct method to extract the perception and comprehension of humans, while being able to continuously extract such knowledge across time, not subjecting to bias at the same time. Of the physiological methods involving non-intrusive eye tracking techniques, they are found to be unable to accurately detect and identify changes in an ATCO's perception and comprehension, as well as being too focused on one aspect of ATCO monitoring task. Therefore, there is a need to develop new methods to extract and represent knowledge of an ATCO's perception and comprehension, such that any changes are detected and identified accurately for multiple tasks across an ATCO's tactical monitoring activity.

Based on the above-mentioned reasons, new methods to extract and represent knowledge are to be developed which can more accurately and adequately measure an ATCO's tactical monitoring activity. These will be addressed in the following chapters.

3. Chapter 3 Dynamic Data Alignment and Timestamp

Synchronisation Model

This chapter proposes a new methodology for real-time dynamic synchronous knowledge extraction and representation of an ATCO's monitoring operation. This methodology comprises a real time eye tracking system which integrates the two sets of activity data in a highly dynamic and synchronous manner in real-time with respect to both spatial and time frames. The application of ATC is used to illustrate this real time eye tracking system and it is based on a "Dynamic Data Alignment and Timestamp Synchronisation Model", which matches the timestamps of the two data streams, aligning them to the same spatial reference frame before fusing them together into a data activity register frame.

The proposed methodology, as seen in Figure 3.1, composed of four main developed modules namely the real time human machine interface input module between ATCOs and radar display monitor, real time data capture module to acquire the data into the system, a Dynamic Data Alignment and Timestamp Synchronisation Model, and the results and analysis module, which enables different form of data interrogation so that analysis of ATCO monitoring behaviour and performance can be realised. Lastly, a record of the analysis can be logged and replayed to the ATCOs in real time. Through this developed framework, it can track eye movements and its associated metrics in real time, derive spatial resolution of up to the object that the ATCO is looking at as well as instantaneous radar capture synchronously, across all dynamic radar updates. A detailed explanation of the proposed real time eye tracking system is described in the following sections.

Figure 3.1. Framework of Proposed Real Time Eye Tracking System

3.1. Real Time Human-Machine Interface Input Module

In this module, information relating to the interaction activity between the ATCO and the radar display is captured via an eye tracking device, its mouse and keyboard input. A remote eye tracker is adopted as it is non-intrusive which minimises disruption of the natural flow of tasks of the ATCOs.

In this setup, the remote Tobii X2-30 is chosen as the eye tracker, while a high fidelity NLR ATM Research SIMulator (NARSIM), is selected to simulate an ATC radar system. Together these systems seek to illustrate the functionality of this real time eye tracking system, together with the Dynamic Data Alignment and Timestamp Synchronisation Model. This aspect will be discussed in greater detail in Section 3.3 and 3.4.2.

To ensure accurate data capture of the synchronised monitoring activity of the ATCO, the physical arrangement of eye tracker and the radar display is first calibrated to ensure that the output pixel co-ordinate values from the eye tracker and radar display are aligned properly. As a 2K screen is used for ATC radar surveillance operations, the remote eye tracker is positioned further in front of the screen to extend the eye

tracker's field of view so that raw eye data on any regions of the 2K screen can be captured. In this study, the distance between the participant's eyes to the eye tracker is set at 55 to 60 centimetres, tilted at 30° from the vertical plane. Eye data is captured within a defined 3D boundary space, which is one that the participant is expected to make his eye ball movements. Measures such as sitting and head position adjustments of the participant throughout the experiment are noted to ensure that the data are captured from within this defined 3D boundary. If this distance is varied, the accuracy and precision of the collected eye data will be affected, resulting in inconsistent eye tracking metrics being computed. Figure 3.2 shows an illustration of this experiment setup, as well as the eye tracker's physical configuration.

Figure 3.2 Illustration of Experimental Setup and Eye Tracker Physical Configuration

Using this configuration, a standard 9 point calibration test to calculate the accuracy and precision of the eye tracker in this setup is conducted, as the accuracy and precision provided by the manufacturers are determined under ideal conditions [101]. Accuracy and precision calculation were made based on the formula provided by Holmqvist et. al [102], while determining the validity of these values at the same time. Validity of eye data is defined as the eye data point lying within the screen area with valid output values, which is indicated by the signal strength of the infrared camera on the eye tracker to a participant's eye. Based on this setup, the accuracy and precision of the Tobii X2-30 was found to be 3.5° and 1.1° respectively for head position within this defined 3D boundary, with good validity of 93.7% [102]. Thus, the velocity threshold is found to be $105^\circ/\text{s}$, while the fixation radius is 35 pixels.

These captured eye data are then sent to the real time eye tracking system at a step interval of 33 ms. This involves receiving eye tracking location and validity values together with its corresponding system timestamp in ms. Hence, a standard 13 digit posix timestamp is used, as it “represents the time expressed in number of milliseconds that have passed since 00:00:00 Coordinated Universal Time (UTC), Thursday, 1 January 1970” [103]. That zero moment on January 1, 1970, known as the epoch, represents the universal start instant in time where the all Unix operating system first used this time representation. This enables a timestamp to be recorded at any instant and it is independent of any other events.

For the radar display data, aircraft position, label and ATCO interaction data have to be captured and sent to the real time eye tracking system. Information like an aircraft’s coordinates in the airspace, label position, the extent of panning, zooming and moving of aircraft label by the ATCO should be present. For this setup, the timestamp of the NARSIM radar data is listed up to ms and is relative to the instant the radar data stream was started. The update rate of the aircraft position data is at every 9.8 seconds, corresponding to the time taken for one radar revolution. Aircraft position in latitude and longitude are recorded. For the ATCO interaction data, actions like the zooming and panning of the radar screen, which corresponds to a distance range and geometric center for the radar display, movement of aircraft label on the radar display are captured. These actions are done using mouse and keyboard inputs, which have to be positioned properly to ensure ATCOs can use them comfortably. Furthermore, such actions can occur at any instant, so the new limit range, geometric centers and label position need to be recorded and updated regularly with their corresponding timestamp, which would later serve as reference values for comparison. Lastly, the different commands and clearances given by the ATCO are also registered along with their corresponding timestamps.

A summary of the data type format of the eye and dynamic radar data in this setup is listed in Table 3.1.

3.2. Dynamic Data Alignment and Timestamp Synchronisation Model

Dynamic Data Alignment and Timestamp Synchronisation model is applied in this real time eye tracking system to synchronise and fuse the eye and dynamic radar data

captured. Subsequently, they are converted to the same unit of measurement and aligned to the same spatial reference frame, taking into account ATCO interaction. These data are then matched accordingly for further analysis. The different stages in this model are illustrated in Figure 3.3.

Table 3.1. Data Type Format of Data Streams sent to the Real Time Eye Tracking System

Raw Data Type	Raw Type Data Format
Raw Eye Data	13 digit posix timestamp, Pixel_X, Pixel_Y, left_pupil_diameter, right_pupil_diameter and validity value
Raw Aircraft Position Data	Radar Data Timestamp, Aircraft Callsign, Latitude, Longitude
Raw Aircraft Label Data	Radar Data Timestamp, Aircraft Callsign, Relative Pixel X value from Track, Relative Pixel Y value from Track
Raw ATCO Interaction Data (pan)	Radar Data Timestamp, Interaction Type, Radar Screen Geometric Centre (Latitude), Radar Screen Geometric Centre (Longitude)
Raw ATCO Interaction Data (zoom)	Radar Data Timestamp, Interaction Type, Range of Radar Screen in Nautical Miles (distance from centre to edge of the screen)
Raw ATCO Interaction (command) Data	Radar Data Timestamp, Interaction Type, Callsign, Value

Figure 3.3. Stages of the Dynamic Data Alignment and Timestamp Synchronisation Model

In the first stage of the proposed model, timestamp synchronisation of the eye and dynamic radar data are conducted. To do so, the raw eye data is first sent to the background of the system, with no data conversion. As the raw radar data is being sent to the system, the first instant when it is sent is recorded and matched to the eye data's timestamp. This instant is recorded using 13 digit posix timestamp, which serves as the common start reference time for both the eye and radar data, thereby synchronising them. Both data streams will then be recorded starting from this instant, also known as the start record instant, synchronising their timestamp respectively. The difference in timestamp between the two data streams at the start record instant is not more than 33 ms, which is equivalent to the step interval of the eye data being sent. Such a difference in time data is acceptable, as the radar data is only sent at a step interval of 9.8 seconds, making this difference in time synchronisation negligible. Furthermore, this is well within the theoretical time difference limit of 250ms, the minimum duration of 1 fixation count, as a one fixation error caused by this synchronisation would only constitute to 2.5% of the overall frame duration, which is within the acceptable error margin of 5%.

The second stage of the proposed model requires the raw data to be converted. Conversions of the raw radar and eye data are performed independently from each

other. For the conversion of radar data, the positional data of the two different moving flight objects, namely the track and label, are computed. Figure 3.4 shows an illustration of the aircraft's track and label, as seen on the radar screen, where the track represents the position of the aircraft in the airspace while the label contains the different flight information related to the aircraft.

Figure 3.4. Illustration of the Track and Label of an aircraft on the Radar Screen

Aircraft track positional data in pixels is converted from raw aircraft position radar data, radar screen centre point latitude and longitude and radar screen range. Such a conversion of the latitude and longitude of the aircraft to its pixel value is calculated based on the distance of the aircraft from the geometric center using the standard haversine formula together with the center pixel value of the screen. Aircraft label positional data is then computed from the raw aircraft label radar data, by adding the relative pixel X and Y value from its track. The pixel value for the 4 edges of the label can then be computed accordingly, as the size of the label is set at 2cm by 2cm on the radar screen regardless of ATCO radar interaction.

For the conversion of eye data, fixation is computed and used as the basic eye metric for this real time eye tracking system, as it illustrates the comprehension of the visual world [104] and it is widely used by researchers for eye tracking studies. A fixation is computed from the eye data using the velocity threshold fixation identification (I-VT) algorithm. This fixation detection algorithm is widely used by researchers in various eye-tracking research [105]. The I-VT fixation detection algorithm, classifies the eye movements based on the velocity of the directional shifts of the eye. A velocity threshold, usually given in visual degrees per second ($^{\circ}/s$), has been set in advance. Any raw eyeball movement data capture that falls below this velocity

threshold is classified as a fixation sample. In this work, a velocity threshold of $105^\circ/\text{s}$ is used, as it corresponds to the eye tracker's accuracy of 3.5° in this setup. A fixation is then computed when consecutive fixation sample adds up to more than 250 ms [106]. The fixation location is then computed by taking the average of Pixel X and Pixel Y values from the fixation sample. It is important to note that, any diversion in monitoring behaviour of the participant causing him to look out of the radar screen will not be counted in this fixation detection algorithm, as it only accounts for eye data that lies inside the radar screen.

In stage three of the proposed model, spatial alignment of both eye and dynamic radar data to the same reference frame is performed, before storing them in a data activity registry framework. Within one radar update of 9.8 seconds, the radar position of the different aircraft is treated to be stationary, which can then be used within the whole radar update if there are no ATCO interactions on the radar screen. However, ATCOs could move the aircraft's label to any position based on their discretion, zoom and pan the radar screen to their viewing comfort, even within one radar update. Such actions will change the position of the flight objects of the radar screen and they need to be factored in, so that the eye tracking metrics would be matched to the respective flight objects, regardless of ATCO interaction on the dynamic radar display. Furthermore, these eye data registered while there were such dynamic changes also needs to be accounted for, so that a fair comparison can be made across these eye data, regardless of ATCO actions. As such, data alignment macros have been developed to address these changes.

To ensure a fair comparison of eye data regardless of ATCO actions, relevant flight data describing the radar image are captured. For the flight label movement on the radar display, the initial set of pixel values of the flight label is registered. These values are then updated and stored as the new flight label position on the radar screen with the respective timestamp, at the instant the ATCO makes such an interaction. As for the zooming and panning actions made by the ATCO, the initial set of range values and the corresponding geometric center of the radar display are also registered respectively. Similarly, these values are updated with their respective timestamp at the instant when the ATCO performs such interaction on the radar screen. An

identifier of these actions is used to indicate the different ATCO actions, which can be prevailing in NARSIM. Such values are necessary to “normalised back” the eye fixation data to its equivalent pixel value with respect to its initial set of display value range, for a fair comparison of the ATCO’s monitoring behaviour across time. Similarly, any radar positional and object data in relation to this new traffic picture can also be “normalised back”. “Normalisation” can be done using Equation (3-1), where d represents the distance moved by the ATCO on the radar display from the initial centre to the new geometric center and α represents the corresponding change in direction of the geometric center.

$$Pixel_{equivalent} = Pixel_{new} * \frac{Range_{initial}}{Range_{new}} + d * (Pixel/Range) * \alpha \quad (3-1)$$

Upon the completion of stage three, any interactions made by the ATCO on the radar screen are factored into the dynamic radar data, while ensuring that the eye and radar data are aligned to the same spatial reference frame. For alignment to the same spatial reference, the real time eye tracking system takes less than 0.003ms for eye fixations and less than 0.5ms for the radar data. This latency in data alignment is insignificant, as a fixation has minimum duration of 250ms and the radar data updates at every 9.8 seconds.

Figure 3.5. Illustration of different data streams occurring

In stage four, data fusion is performed where a timestamp captured is used to integrate both sets of eye and dynamic radar data synchronously. As the series of events from both of these data streams occur at different instances randomly, these two data streams have to be matched to each other in order to determine if an eye fixation is on a flight. Figure 3.5 shows the different updates between two sets of data streams of eye metric fixations and radar traffic display data captured during the monitoring interaction of an ATCO.

To harmonise an eye fixation with a flight object, both sets of data (eye fixation and flight object) have to be matched at the same instant. As the human's eye is attracted to any new visual stimulus [107], if there is no change in dynamic radar data, any new fixation data is said to be looking at the original image, which corresponds to the same positional data of the flight objects, before an event update. Hence, the process of matching the synchronised timestamp and that of spatially aligned positions between eye and radar data streams is illustrated in a flowchart, as seen in Figure 3.6.

Upon matching the two data streams through data fusion, a fixation can then be traced to the different flight objects to determine if the ATCO was looking at them. Upon completion, the model is deemed to have successfully synchronised the timestamps of the dynamic display images in the form of a dynamic radar display, together with the eye data.

Figure 3.6. Flowchart of Data Fusion Process

3.3. Results and Analysis Module

To trace the fixation to an exact flight object, suitable size boundaries around the aircraft's track and label on the radar screen are set. The standard notation of an aircraft's track is a 3mm diameter circle and an aircraft's label is a 2cm by 2cm square on the radar screen, which corresponds to a circle of a 12 pixel diameter and 82 by 82 pixel square respectively. To account for the fixation tolerance of 35 pixel radius, these flight object sizes have been revised to a 70 pixel diameter and 230 pixel diameter circle for the track and label respectively. For any fixation which is within these boundaries, the ATCO is deemed to be looking at the flight object.

In this work, four suitable eye ball movement metrics have been successfully implemented for assessing ATCO's visual observation and monitoring. These are listed in Table 3.2 along with its definitions.

Table 3.2. Eye Tracking Metrics, Definitions and meanings

Eye Tracking Metric	Description
Fixation Count	Count of number of fixations
	A measure of underlying processing efforts [108]
Fixation Duration	A longer fixation duration indicates the longer processing time needed [104]
Gaze Duration	Sum of all successive fixations
	Processing time used for perceiving the information [109]
	Measure of difficulty in processing information [110]
Fixation Scan Sequence	A scanpath formed by joining fixations in a chronological order

The computed monitoring performance metric, operating under the specified set of conditions are compiled and results are then stored in a data activity registry framework. Figure 3.7 shows an example of a radar frame image, which is a single instance data interrogation based on the finest time resolution of one radar update, together with the specified set of eye tracking metric. A fixation is represented by one black solid square on its corresponding pixel location, while the varying colour tone of the square bit shows the fixation duration, whereby the darker the colour, the longer is the fixation duration. The duration of every fixation is scaled by applying common logarithm, thus ensuring that all fixations are visible in every frame. Therefore, in Figure 3.7, the fixation count is 8, with a gaze duration of 5245ms, which is shown in the top left corner. Fixation scan sequence is also plotted by joining the different fixations and labelling them in chronological order. The circles and

squares in Figure 3.7 represent the track and label of an aircraft respectively, as seen by the ATCO on the radar screen along with their corresponding callsigns. Other radar image information like the airways and its flight direction are also illustrated. At the top left corner, the radar update and fixation recording time interval is also shown, together with the centre coordinate values and range of the radar screen, to indicate any zooming and panning action by the ATCO.

Figure 3.7. Single Instance Data Interrogation on one Radar Update

3.4. Concept and Test Validation

Concept test validation is performed to highlight the proposed Dynamic Data Alignment and Timestamp Synchronisation Model, in the real time eye tracking system used to address the five features as described in Table 2.1. These features are

namely, the synchronised timestamp of eye and display data, the use of dynamic display data, the alignment of eye, display data and user input spatially, and the ability to account for dynamic display data both spatially and in time. In this illustration, the simulation data in the radar display is used as the dynamic display data in the ATC application.

3.4.1. Experimental Design and Scenario Definition

A test scenario, consisting of aircraft flying across crossing points was developed, to illustrate the proposed Dynamic Data Alignment and Timestamp Synchronisation Model in facilitating air traffic monitoring activities. Crossing point monitoring, a common traffic management activity, refers to how ATCO monitors (looks) at the aircraft before they cross with another aircraft in the airspace for conflict detection tasks. A crossing event in the airspace is defined as 2 aircraft crossing a waypoint spatially within 10 seconds, which is further illustrated in Figure 3.8. For each test scenario, inputs from experienced ATCOs are considered, with the aim of showcasing the new measurements enabled. Hence, a total of 59 aircraft of various cruising speed and altitude, flying randomly in the airspace that mimic operational air traffic were designed, consisting of combination of 20 crossing points at the different time and location. Each experimental session is made up of this scenario, which lasts for one hour and a total of 10 experimental sessions were conducted in this study.

Figure 3.8. Pictorial illustration of a crossing event

3.4.2. Experimental Setup and Test Runs

Figure 3.9 shows a standard Controller Working Position (CWP), consisting of 2K radar screen used to display air traffic data, together with the other equipment used, which was mentioned in Section 3.1. The metrics collected are then relayed to the Thales TopSky-HF software, a proprietary user interface software, which enables easy data recording and manipulation. The data collected composed of different expertise levels of test participants [81]. Pseudo pilots were deployed to facilitate the flow of this experiment, which were conducted with various test participants, using the scenarios defined, arranged in a random order.

Figure 3.9. CWP with equipment required

3.5. Discussion of Results

An evaluation on the features of the proposed Dynamic Data Alignment and Timestamp Synchronisation Model are performed. In addition, the system is used to evaluate two common radar ATCO monitoring activities.

3.5.1. Evaluation of Proposed Model

Using the 10 experimental sessions conducted, five distinct features of the model are evaluated in this section and the same results are achieved. On the feature of 'uses dynamic display data', this model can successfully receive both sets of dynamic data from the radar display and eye data, which updates at every 9.8s and 33ms respectively.

On data synchronisation of radar and eye data, both data sets have timestamps generated from the same computer system clock. Hence, no timing difference in the timestamps is envisaged between these two sets of data. It is also noted that the time delay due to the transmission of data is negligible.

Evaluation of the feature, spatial alignment of the eye and radar data is performed by checking the exactness of the pixel location value and aspect ratio of both the eye image plane and radar plane. On the eye image plane, the pixel value of its centre corresponds to the same centre of the radar display. Such is also the case for the 4 corner points of the eye image plane and the radar plane on the radar display. For the aspect ratio, both the eye image and radar plane are found to be the same, with 2048 pixels for 50 centimetres, in both horizontal and vertical planes. As a result, it allows proper matching of the pixel values in both the eye image and radar plane, with the fixation tolerance being accounted for.

Lastly, the two features of accounting for changes in the dynamic radar data both in time and space are evaluated. This model can compute and output the different aircraft pixel location data at every radar update of 9.8s, which corresponds to its location on the radar screen. In addition, any dynamic radar interaction from the participants are also captured accordingly, with its respective timestamp and corresponding pixel location value.

From the above evaluation, the proposed system can meet all the five required features. In addition, for the 10 experimental sessions conducted, an average of 2799 fixation count were registered, equating to 2325.6 seconds looking at the radar screen over a one-hour duration. Of these times spent fixating at the radar screen, on the average, 75% of the time are spent looking at flight objects, in which the aircraft's label constitutes to 65% of these flight objects fixated. Such information on the participant's monitoring behaviour is enabled with the proposed model, which can also be enabled on other eye tracking system. Further discussion is made in the ensuing sections to validate its possible use in the field of ATC.

3.5.2. Discussion of New Analysis Results

Two test analyses on crossing point monitoring task are performed based on the Dynamic Data Alignment and Timestamp Synchronisation Model. They are fixation

count on any flight object (track or label) at a fixed crossing point and the instantaneous and duration based analysis of how participants monitored the flight objects of a dynamic aircraft on the radar display.

3.5.2.1. Analysis 1 – Fixation Count of Dynamic Flight Objects Movement over a Waypoint

In this test, the task is to determine and analyse the fixation count on any flight object (track or label) over a particular crossing point on the radar screen. Table 3.3 shows the location of crossing point in the default position on the radar display.

Table 3.3. Characteristic of Waypoint

Crossing Point	Pixel X Value	Pixel Y Value
CP1	896	982

For this crossing point, the tolerance used is 35 pixels as earlier highlighted in Section 3.3. Thus, for any fixation that is within a 35 pixel radius from the crossing point, it is deemed that the participant is fixating in this region, as seen in Figure 3.10. This means that if an aircraft flight object appears within this region via radar interaction or aircraft movement across time, and a fixation lands in this region, it is inferred that the test participant has fixated on the flight object.

10 sample crossing point instances of the scenario are chosen from various participants for this test. Fixation count at the crossing point, ‘CP1’, was computed for these samples, together with the number of fixations with and without aircraft flying pass ‘CP1’. Results of this computation are shown in Table 3.4.

Figure 3.10. Illustration of Crossing Point Tolerance for determining a fixation on crossing

Table 3.4. Fixation Count characteristics on 10 sample crossing points

	10 Sample Crossing Point									
	A	B	C	D	E	F	G	H	I	J
Total Fixation Count in general	1	3	4	0	3	5	0	2	3	5
Fixation Count on crossing point with aircraft flying pass it	0	0	2	0	0	3	0	0	1	2
Fixation Count on crossing point with no aircraft flying pass it	1	3	2	0	3	2	0	2	2	3

From Table 3.4, it is first noted that fixations within the crossing point region are detected and computed from various experimental sessions. Apart from this, the presence of dynamic flight object (aircraft) flying past the crossing point when the fixation is exhibited can now be enabled. Furthermore, a variation of fixation counts and fixation on an aircraft at the crossing point amongst participants are also observed. It is noted that participants in 4 such samples are fixating on ‘CP1’ with aircraft flying

pass it. This possibly indicates that participants involved in these runs are interested to look at the aircraft as it was at the crossing point.

These results show that the proposed model can detect fixations on a crossing point and if a dynamic flight object is present when a fixation is exhibited. As a result, measurements taken from participants across various experimental sessions also highlight variations in their monitoring behaviour. It must also be noted a similar analysis is enabled when the Dynamic Data Alignment and Timestamp Synchronisation Model is applied on other eye tracking system.

3.5.2.2. Analysis 2 – Instantaneous and duration based analysis of how participants monitored the flight objects of a dynamic aircraft on the radar display

In the second test, an analysis is performed on a crossing event where two aircraft are to fly towards “CP1”, the same crossing point as in Table 3.3. A study is made on the track and label of a particular aircraft, ‘X’ with respect to the crossing point, ‘CP1’ being the next waypoint in its flight route. The system can extract the time frame of occurrence which is between frames 66 to 79. 10 crossing point samples of “CP1” are chosen for this test, whereby the fixation count and fixation duration in each of these frames are thus compiled and shown in Table 3.5. An instantaneous frame analysis of the monitoring behaviour on aircraft ‘X’ for each of these 10 crossing point samples can also be performed. A similar analysis can also be done for aircraft Y, the other aircraft flying towards “CP1” accordingly. Table 3.5 shows the total fixation count and gaze duration on Aircraft X’s track and label from frame 66 to 79.

Table 3.5. Total Fixation Count and Gaze Duration of Aircraft X's flight objects for all participants

	Label		Track	
Sample ID	Total Fixation Count	Gaze Duration (ms)	Total Fixation Count	Gaze Duration (ms)
A	5	4826	2	1865
B	15	14512	3	564
C	17	19866	14	13666
D	0	0	0	0
E	17	15239	3	1021
F	22	23974	14	12501
G	4	2853	4	4685
H	4	4014	3	634
I	11	4576	4	2109
J	8	6018	3	774

From Table 3.5, fixations by participants were made in 9 out of the 10 crossing points when an aircraft is flying towards a crossing point. One participant did not fixate on Aircraft X at all. It was also found that 4 out of the remaining 9 participants spent more than 10000 ms on both the track and label of Aircraft X combined. This suggests that they are more focused on the movement of Aircraft X across the crossing point. Hence, the different way which participants monitor Aircraft X can be deduced. It is also observed that participants' fixation duration on the flight label is 1.45 to 25.7 times longer, as compared to its track. An inference is that the flight object, label, is more important to the participants when an aircraft is flying towards a crossing point.

This would be owing to the fact that the label contains the crucial flight characteristics of Aircraft X. A longer gaze duration on Aircraft X's label may mean a longer time is needed to process the information, thereby suggesting that the label could be used to evaluate the information processing of a participant. Therefore, new observations regarding the monitoring behaviour of a participant, as seen in their fixation on the dynamic flight objects during the time of occurrence can be made. Similarly, variations in the monitoring behaviour of the participants were noted and it is found that participants in general tend to monitor an aircraft's label when it is flying across a crossing point.

In addition, the cumulative fixation duration curve for all 10 crossing point samples on the label and track of Aircraft X along the same flight path were computed accordingly, as seen in Figure 3.11 and 3.12 respectively.

Figure 3.11. Cumulative Fixation Duration on Aircraft X's Label by all participants

In Figure 3.11, participants in 7 of the 10 sample crossing points were fixating consistently on Aircraft X's label as it flies towards the crossing point, from frame 66 to 79. This could likely indicate that participants in these 7 runs are checking Aircraft X's flight characteristics regularly before it crosses this crossing point, as most participants performed such monitoring several times. In addition, participants in sample crossing point G only started fixating on the label at frame 76, thereby indicating a sense of late monitoring. In Figure 3.12, participants in 6 of the 10 sample crossing points spent their time fixating on Aircraft X's track in just one step interval from frame 66 to 79, while participants in 3 out of the remaining 4 spent a majority of their fixation duration before frame 75. This meant that most participants only prefer to look at the aircraft's track once, while other participants tend to be more consistent. This indicates that some participants may not be observing as much as others, as in the cumulative fixation duration profile on both track and label. Furthermore, it shows that an aircraft's track could likely serve the purpose of representing an aircraft's position, with no other vital information present to the participants. Hence, the monitoring behaviour and strategies of the participants were enabled and represented in these analyses, together with participants who performed late monitoring on these aircraft. This form of analysis is presently not possible given the current eye tracking systems.

For time-based pattern and trend analysis, an eye heatmap, a graphical representation of the distribution of fixation duration on a radar display from frame 66 to 79, can be generated for each sample crossing point. Figure 3.13 shows a fixation duration heatmap for sample C from frame 66 to 79, with the position of Aircraft X on the radar display being highlighted. The varying colour tones denote the difference in fixation duration over the radar display. In this figure, the lighter colour denotes a longer fixation duration. From Figure 3.13, it is observed that in sample C, the participant was monitoring aircraft X along its airway, with an extra focus along the crossing point region. Furthermore, different heatmap displays highlighting various monitoring pattern could be also registered and compared for each of the 10 sample crossing points, to represent and understand the differences in the monitoring behaviour.

Figure 3.12. Cumulative Fixation Duration on Aircraft X's Track by all participants

As a result, greater clarity of a participant's monitoring behaviour is enabled, as the exact flight object which a participant is fixating on, at any instant can be identified. Such knowledge on the monitoring behaviour of a participant is important in the tactically monitoring activity of an ATCO. Further studies could thus be made to analyse and determine the monitoring heatmap and behaviour of individual participants.

Figure 3.13. Fixation Duration Heatmap on Aircraft X from frame 66 to 79

3.6. Summary of Findings

In this chapter, a new real time eye tracking system which integrates two sets of activity data in a highly dynamic changing and synchronous manner with respect to both spatial and time frames, has been developed. This system is based on a “Dynamic Data Alignment and Timestamp Synchronisation Model”, which is able to synchronise the timestamp of the eye and dynamic display data, align both of these data spatially, while taking into account changes in space and time of the dynamic display data. This allows knowledge for a deeper understanding of an operator’s performance to be extracted with finer resolution, together with the good level of synchronisation.

Test validation using 10 experimental sessions conducted shows that the proposed model can satisfy all the 5 desired feature requirements as set out for synchronous dynamic monitoring in real time with superior finer resolution than the reviewed systems. Similar results were achieved for each of these sessions. This is seen in the pixel values of the two data streams that are matched exactly with no time delay, as they are referenced from the same computer system clock. Furthermore, the latency

in the transmission of data is insignificant, as the difference in timestamp between the two data streams at the start record instant is not more than 33 ms, while the time taken to align these data streams to the same spatial reference frame is less than 0.003ms for eye fixations and less than 0.5ms for the radar data of all sessions.

From the 10 experimental sessions conducted, an overall breakdown of a participant's monitoring behaviour is also enabled. Participants are found to register an average of 2799 fixations lasting for 2325.6 seconds on the radar screen over a one-hour duration. Furthermore, participants were found to spend 75% of the time looking at flight objects on average, with the aircraft's label comprising of 65% of the flight objects fixated. It is important to note that such statistics were not extracted from previous systems.

Two test analyses that seek to determine the fixation count on any flight object (track or label) at a fixed crossing point and the instantaneous and duration based analysis of how participants monitored the flight objects of a dynamic aircraft on the radar display were performed. Results show that the proposed system is able to capture and compute fixation count on any flight object (track or label) at a particular fixed crossing point. It is also able to compute both at an instantaneous time frame and over a specific set of time frames. Analysis of individual monitoring activity by participants on a dynamic aircraft on the radar display can also be conducted. Results from these analyses show that this system can distinguish and show variations in the monitoring behaviour of participants. This is critical as present ATC systems that do not possess such capabilities in distinguishing the monitoring behaviour between ATCOs, as seen in the frequency and distribution of fixation duration on an aircraft's flight object across time.

Hence, new knowledge on the monitoring behaviour of ATCOs are successfully extracted and represented, paving the way for a new horizon in electronic surveillance and other similar type of application requirements.

4. Chapter 4 Tactical Complexity Calculation

This chapter proposes a tactical complexity approach that makes use of all the six desired features, as described in Section 2.2.1, where instantaneous aircraft data are captured together with its intent, covering a broad spectrum of air traffic situations with meaningful representation of aircraft characteristics, while determining the spatial complexity in real time (both instantaneous and duration of time) of any designated region(s) on the radar screen. In addition, this approach should also consider the dynamic air traffic flow and its network characteristics in real-time so that tactical measures can be taken by ATCOs. It is important to note that tactical complexity refers to the difficulty of the airspace that is perceived by the ATCOs, from the various flight configuration, and it has no relation to their respective conflict prediction based on trajectory. Hence, the higher the level of tactical complexity, the more vigilant an ATCO would need to be.

The approach makes use of data obtained from current and projected aircraft's position and trajectory, which involves three main steps. These are (1) the establishment of the flight conflict shape movement for pairwise traffic complexity Conflict Activity Level (CAL), (2) evaluation of instantaneous CAL calculation and (3) the proposed CAL-Separation Axes Theorem (CAL-SAT) model for the time projection of tactical complexity. Besides being able to evaluate the overall and regional complexity on the radar screen, the CAL-SAT model can also be used to assist in the forecasting and planning of ATCOs' control strategies based on the traffic flow and network characteristics. Hence, a new CAL time profile feature between two aircraft, assuming the aircraft pair maintain their current trajectory, based on their instantaneous flight characteristics can also be generated.

4.1. Flight Conflict Shape Movement

The flight conflict shape movement represents the extent to which the aircraft would be in opposition with other traffic or exogenous factors such as weather and emergency situation. In this work, the tactical conflict shape movement of an aircraft flying in an airspace is established based on its current position and trajectory, its likely angle of deviation from its current trajectory and the safety standards imposed in the airspace that it is flying.

Figure 4.1 shows the lateral and vertical views of the derived flight conflict shape movement. In the lateral view, the conflict shape movement consists of the front and back portions. The front portion highlights the forward movement of the aircraft designated by an arrow symbol which denotes its current position and trajectory (centreline). The length and direction of the centreline corresponds to the speed and heading of the aircraft, respectively. As the aircraft may deviate from its trajectory, this is accounted for by a drift angle, θ , to the left and right of the centreline giving rise to an arc sector [111]. To meet the Required Navigational Performance (RNP) standard of the airspace, a rectangular block is used to form the lateral region around the airspace at the front portion of the aircraft. Any deviation of lateral aircraft movement is accounted for in this rectangular block whenever RNP standards are larger than radar surveillance lateral separation distance between aircraft. On the back portion of the aircraft, this is represented by a semi-circle, taking into account the wake turbulence separation standard.

Figure 4.1. Establishment of an aircraft's Conflict Shape Movement

In the vertical view, the rate of climb/descent of the aircraft is determined based on the aircraft vertical trajectory and the corresponding vertical velocity of the aircraft. This vertical trajectory is derived from the aircraft's current and cleared Flight Level (FL). The angle of deviation of β (upwards and downwards) can subsequently be derived [111]. In addition, the aircraft is encircled by a rectangular block to take into account the vertical separation standard. In this case, a Reduced Vertical Separation Minimum (RVSM) standard of 10 FL is used as the vertical separation of the airspace.

To cater for different conflict time scenarios, the shape can consist of two main profiles; an extended one by a larger factor and a unit factor. This is shown in Figure 4.2 for both lateral and vertical views. In Figure 4.2, X represents the current ground speed and heading of the aircraft, while $2X$ corresponds to an extended factor of two times the speed. Ground speed is used as it is a direct information source from the radar screen for ATCO monitoring tasks. An extension of X is used as ATCOs tend to project the traffic situation in the tactical monitoring [19, 69]. A choice of 2 is used for the illustration of this concept.

Figure 4.2. Extended Shape of Aircraft

4.1.1. Pairwise Traffic Complexity Conflict Activity Level (CAL) Evaluation

The first step seeks to evaluate the degree of traffic complexity via CAL between an aircraft pair within a specified Region(s) Of Interest (ROI). A ROI is a user defined region that maps out a certain area under ATC review or surveillance within the radar display, which can vary in location, shape and size. In this work, the ROI is a circle with a point location centre. Through a series of commonly used Boolean algebra operations and location co-ordinates over a spatial volume, the proposed approach computes and determines the degree of overlap between the aircraft pair based on their corresponding 3D conflict shape movements. An overlap occurs whenever the flight conflict shape movement of the aircraft pair intersects due to their respective lateral and vertical trajectories. As opposed to 3D volumetric analysis, this approach was selected as it has the potential to perform quick and straightforward computation of complexity.

In this work, the degree of overlap is represented by four CALs having a score ranging from 0 to 3. A score of “0” indicates the least complexity as no aircraft is present. A

score of “1” indicates low complexity which register the presence of an aircraft pair but with totally no overlap in the 3D aircraft shape movement. Viewed from either a lateral or vertical plane perspective, one of its views would not have any overlap. A score of “2” indicates high complexity as an overlap is present in the 3D aircraft shape movement. These instances would either be partial overlap of aircraft shape movement at both lateral and vertical view planes at any angle and orientation, or a total overlap of aircraft shape movement in the lateral view plane with a partial overlap at any angle and orientation at the vertical view plane or vice versa. As for a score of “3”, this indicates the highest complexity as the 3D aircraft shape movement of one aircraft is wholly inside of the other in both lateral and vertical view planes. As this is a representation of tactical complexity which is independent of an aircraft’s conflict profile, a CAL value of 2 and 3 would not necessary lead to a conflict between the aircraft pair.

Upon determining the pairwise CAL evaluation, CAL can then be applied for instantaneous evaluation of multiple aircraft on the whole radar screen and also to determine the CAL time profile between the different aircraft pairs based on current aircraft characteristics. These CAL calculations will be described in the following sections.

4.2. Instantaneous CAL Calculation

For instantaneous CAL evaluation, a CAL matrix table is first established, as it represents a compilation of various CAL scores for the different aircraft pairs within the specified ROI at an instance. This is highlighted in Figure 4.3 where four aircraft are found to be randomly distributed on the radar at a particular time frame. Each aircraft is assigned a label number ranging from 1-4. The different parameters of individual aircraft are shown in Table 4.1.

Figure 4.3. Example scenario - A set of four aircraft registered in a radar at a particular time frame

Table 4.1. The Set of Aircraft Operating Parameters used in the Example Scenario

Aircraft ID	Heading (°)	Drift Angle (°)	Speed (knots)	Current Flight Level	Cleared Flight Level
1	90	5	300	320	320
2	240	5	300	325	310
3	270	5	200	370	370
4	270	5	350	365	380

Based on a pairwise evaluation and mapping of these aircraft to the traffic complexity CALs, the pairing CAL scores can be tabulated into a matrix for the ROIs, as shown in Table 4.2. From Table 4.2, the approach could identify that the aircraft pairing 3 and 4 is at the highest complexity CAL of 3. In this instance, aircraft 3 is found to be wholly inside the shape movement of aircraft 4 both laterally and vertically, as aircraft 4 is climbing past the cruising FL of aircraft 3 at a higher speed. Immediate

attention is therefore needed. A CAL of 2 is observed between aircraft pairing 1 and 2, as the 3D shape movement between aircraft pairing 1 and 2 has a partial overlap laterally and a total overlap vertically, therefore requiring some degree of monitoring.

Table 4.2. CAL Matrix Table in example scenario from the pairwise aircraft comparison

	Airspace	Aircraft 1	Aircraft 2	Aircraft 3	Aircraft 4
Airspace	-	1	1	1	1
Aircraft 1		-	2	0	0
Aircraft 2			-	0	0
Aircraft 3				-	3
Aircraft 4					-

4.2.1. Overall complexity ROI score

Traffic complexity at static time frames can be performed at different ROIs. Figure 4.4 shows a scenario of a set of four aircraft with three ROIs indicated. The overall CAL score and its mean for the different ROIs (A-C) for the three ROIs can be found in Table 4.3. Equations (4-1) and (4-2) are self-developed equations used to compute these CAL values.

$$\begin{aligned}
 &\text{Overall CAL Score} \\
 &= \sum_{i=0}^3 \text{Total Number of Overlap Counts in } CAL(i) \quad (4-1) \\
 &\quad * CAL \text{ Score}(i) \\
 &\quad \text{where } i = 0, 1, 2, 3
 \end{aligned}$$

$$\begin{aligned}
 &\text{Mean CAL Score}_{\text{region/overall}} \\
 &= \frac{\text{Overall Complexity Score}}{\text{Number of Overlap Counts}_{\text{region/overall}}} \quad (4-2)
 \end{aligned}$$

Figure 4.4. Example scenario - a set of four aircraft having three different ROIs at a particular time frame

Table 4.3. Breakdown number of CAL scores in the example scenario

ROI	CAL = 0 (No aircraft)	CAL = 1 (Distinct Separated)	CAL = 2 (Partial Overlap)	CAL = 3 (Fully Overlap)	Overall CAL Score	Mean CAL Score _{region}
A	0	4	1	1	9	1.5
B	0	2	1	0	4	1.3
C	0	0	0	0	0	0

From Table 4.3, one can observe that the overall CAL score and mean CAL score in ROI(A) is the highest and ROI(C) the lowest. A higher score denotes greater complexity in a given traffic scenario leading to a likely higher level of conflict being encountered. This is within expectations as aircraft in ROI(A) operate at a higher CAL score than ROI(C) with no aircraft in it. Besides this, when comparing ROI(A) and ROI(B), the higher complexity CAL in ROI(A) is due to aircraft 3 and 4 lying outside of ROI(B) and operate at a higher CAL. Flight adjustment may need to be

made between this aircraft pair where appropriate. From the analysis, the approach is able to readily highlight the critical ROI to the ATCOs, thereby enabling them to better focus their tasks at hand.

4.2.2. Concept Test Validation

For the proposed CAL complexity model, validations are carried for various traffic scenarios and then compared at factor analysis and model analysis levels.

4.2.2.1. Experimental Setup

An experimental setup was designed to test the CAL concept. A real-time simulator, the Nationaal Lucht-en Ruimtevaartlaboratorium (NLR) ATM Research SIMulator (NARSIM), was used to simulate various air traffic scenarios in real time. Aircraft position data, current and future flight trajectory data were extracted and used to compute the CAL complexity score tactically, by using a real-time post processing server [81, 112, 113].

To test and validate the concept of CAL, traffic scenarios were simulated and experimental tests were conducted using the setup described. Discussion of this concept test validation is made in the next section.

4.2.2.2. Factor analysis level validation of proposed CAL complexity model

A factor analysis level validation of the proposed CAL complexity model with other complexity models is discussed in this section. Table 4.4 shows three commonly used factors found in these approaches to evaluate traffic complexity within a designated airspace. Assuming all other factors remain constant, a reduction in displacement between aircraft, an increase in aircraft speed or an increase in conflict risk between aircraft were found to result in greater traffic complexity. A “-” sign indicates that the approach did not account for this factor. Like all the other complexity models, the proposed CAL model registered similar trends, as seen in the change of complexity level in all three factors studied.

Table 4.4. Outcome of Traffic Complexity Model Output due to changes in the key factors

Complexity Models	Reduction in displacement between aircraft ¹	Increase in velocity of aircraft ²	Rise in conflict between aircraft ³
DD and its variants ^a	↑	-	↑
Masalonis's model ^b	↑	↑	↑
Chatterji's model ^c	↑	↑	-
Boag's Relational Complexity ^d	↑	↑	↑
Radanovic's model ^e	↑	↑	↑
Delahaye's model ^f	↑	↑	↑
Proposed CAL model	↑	↑	↑

¹ Reduction in displacement between aircraft indicates that the aircraft are closer to each other in the airspace.

² Increase in velocity of aircraft indicates that the aircraft are flying at an increased speed.

³ Rise in conflict between aircraft indicates that an increase in conflict configuration among aircraft in the airspace.

^a Laudeman et al. (1998), Kopardekar and Magyarits (2002; 2003), Kopardekar et al. (2009), Sridhar et al. (1998)

^b Masalonis et al. (2003)

^c Chatterji et. al (2001)

^d Boag et al. (2006)

^e Radanovic et al. (2017)

^f Delahaye and Puechmorel (2000), Puechmorel and Delahaye (2009)

4.2.2.3. Model analysis validation of proposed CAL complexity model

On model analysis, the proposed CAL complexity model was compared with Delahaye and Puechmorel's (2000) model, one of the most compliant models, using a set of traffic scenarios. As these scenarios showcase the aircraft's intent as well as presented instances across a broad spectrum of air traffic situations, only a comparison with Delahaye and Puechmorel's (2000) model is made here. Such information was not available or evident in the approaches by Boag et al. (2006) and Chatterji and Sridhar (2001).

4.2.2.3.1. Description of Traffic Scenarios

Four sample traffic scenarios were used for the calculation of complexity, which are:

- Scenario 1: A random flow of air traffic, consisting of 40 aircraft with random initial position and velocity was generated. In this work, only one random scenario was studied and used as an illustration.
- Scenario 2: A parallel flow of air traffic, consisting of 40 cruising aircraft at the same FL, moving in the same direction.
- Scenario 3: A right angle crossing air traffic flow, consisting of 40 aircraft crossing at waypoints with intersecting lateral and vertical trajectories, inducing conflict.
- Scenario 4: A low angle crossing of 15° (between the low angle range of 1° to 15°) air traffic flow, consisting of 40 aircraft crossing at waypoints with intersecting lateral and vertical trajectories, inducing conflict [114].

These scenarios are based on those highlighted in Delahaye and Puechmorel's (2000) work to perform complexity computation. The geometric representations of the scenarios are also illustrated in Figure 4.5. In their work, complexity values were only computed based on the initial position and velocity at the start of each scenario.

For all the scenarios, the traffic is assumed to be moving in a regular, orderly manner, using the same aircraft type. Airways constructed in the scenario observed the RNP10 navigation standard. Other fixed parameters that affect CAL shape are listed in Table 4.5, where the drift angle of the aircraft while cruising is set at 5° [115].

Table 4.5. Fixed parameters of aircraft's shape

Aircraft Characteristics	Basic Shape Feature	Value
Cruising Speed (knots)	Centreline Length	400
Drift Angle	Lateral deviation	5°

Figure 4.5. Illustration of Validation Scenario

4.2.2.3.2. Model analysis validation results of proposed CAL complexity model

To validate the proposed CAL complexity model, the overall and mean complexity scores of the CAL model are used for comparison with other established models owing to the amount of information available in the cited papers.

For the proposed CAL complexity model, overall and mean CAL scores are calculated for the four different traffic scenarios, using initial position and velocity at the start of the scenario (frame 1). The overall and mean CAL score at frame 1, together with its corresponding rank from highest to lowest (4 to 1) for each of the four scenarios are shown in Table 4.6. The results are consistent with those of Delahaye and Puechmorel (2000) who ranked the four scenarios in descending order

of complexity as low angle crossing, right angle crossing, random flow and parallel flow, as seen in Table 4.6.

Table 4.6. Complexity Model and Complexity Score comparison of all 4 scenarios at frame 1

Complexity Models	Indicators	Scenario 1 (Random Flow)	Scenario 2 (Parallel Flow)	Scenario 3 (Right Angle Crossing)	Scenario 4 (Low Angle Crossing)
Proposed CAL Complexity Model	Mean CAL Score_{overall}	1.1720	1.1390	1.2878	1.5817
	Overall CAL Score	961	934	1056	1297
	Ranking	3	4	2	1
Delahaye's Complexity Model	Entropy score	8274	0	64173	487267
	Ranking	3	4	2	1

4.3. CAL Time Profile Calculation – CAL-Separation Axes Theorem (SAT) (CAL-SAT) Model

To generate the CAL time profile, Figure 4.6 shows the schema of the proposed CAL-SAT model which consists of four main phases. The 3D aircraft shape movement is first defined, by extracting the relevant flight information and constructing the flight conflict shape movement. Separation Axes Theorem (SAT) is then used to formulate the flight conflict shape movement profile across time. Pairwise computation of CAL vertically and laterally is subsequently performed concurrently before obtaining the overall CAL value. After that, the CAL time profile curve can then be generated. Each of these phases would be explained in detail in the ensuing sections.

Figure 4.6. CAL-SAT Model Schema

4.3.1. Phase 1: Extracting of Flight Information for 3D CAL Shape Profile Construction

To construct the flight conflict shape movement, pertinent information needs to be extracted from the radar flight data display. Figure 4.7 illustrates the different key vertices of aircraft X to form a flight conflict shape movement (convex moving object), C_X . This is denoted by $C_X = \langle P_{BX1}, P_{BX2}, P_{BX3}, P_{TX1}, P_{TX2}, P_{TX3} \rangle$ with P_{BX} showing the current position of aircraft X, while subscripts 2 and 3 represent the other vertices and subscripts T and B denote the top and bottom surfaces respectively.

Figure 4.7. Representation of 3D Aircraft Shape Movement as a 3D Convex Moving Object

To map the flight information of the moving aircraft to a flight conflict shape movement, data about Aircraft X needs to be first derived as in (4-3).

$$\begin{aligned} \text{Flight Conflict Shape Movement, } C_X & \quad (4-3) \\ & = f(P_X, V_X, HDG_X, CurrentFL_X, CurrentFL_X, t) \end{aligned}$$

where

- P_X represents the initial Position (P) of Aircraft X
- V_X and HDG_X represents the Velocity (V) in knots and the Heading (HDG) of Aircraft A respectively
- $CurrentFL_X, ClearedFL_X$ represents the current and cleared Flight level (FL) of Aircraft X respectively
- t represents the elapsed time which the aircraft has travelled in the airspace, from any specified reference starting time

This set of information can be obtained from the radar flight data display. As the heading of the aircraft is with reference to the Earth's magnetic north, there is a need to convert them into polar coordinates, which can be achieved using the following conversion formula.

$$\text{If } \left(HDG < \frac{\pi}{2} \right),$$

$$\theta = \frac{\pi}{2} - HDG$$

else,

$$\theta = \frac{5\pi}{2} - HDG$$

Equations (4-4) to (4-9) are then used to map the derived data from (4-3) to represent the flight conflict shape movement profile across time. A similar procedure can also be performed on aircraft Y, to obtain the set of 3D convex moving object vertices for aircraft Y, $C_Y = \langle P_{TY1}, P_{TY2}, P_{TY3}, P_{BY1}, P_{BY2}, P_{BY3} \rangle$.

$$P_{BX1} = P_X + t(\overrightarrow{V_X})$$

$$\begin{bmatrix} X_{BX} \\ Y_{BX} \\ CurrentFL_{BX} \end{bmatrix} = \begin{bmatrix} X_X \\ Y_X \\ CurrentFL_X \end{bmatrix} + t \begin{bmatrix} V_X \cos \theta_X \\ V_X \sin \theta_X \\ 0 \end{bmatrix} \quad (4-4)$$

$$P_{BX2} = P_{BX1} + 2V_X * \begin{bmatrix} \cos(\theta_X - \beta) \\ \sin(\theta_X - \beta) \\ 0 \end{bmatrix} \quad (4-5)$$

$$P_{BX3} = P_{BX1} + 2V_X * \begin{bmatrix} \cos(\theta_X + \beta) \\ \sin(\theta_X + \beta) \\ 0 \end{bmatrix} \quad (4-6)$$

$$P_{TX1} = P_{BX1} + \begin{bmatrix} 0 \\ 0 \\ ClearedFL_X - CurrentFL_{BX} \end{bmatrix} \quad (4-7)$$

$$P_{TX2} = P_{TX1} + 2V_X * \begin{bmatrix} \cos(\theta_X - \beta) \\ \sin(\theta_X - \beta) \\ 0 \end{bmatrix} \quad (4-8)$$

$$P_{TX3} = P_{TX1} + 2V_X * \begin{bmatrix} \cos(\theta_X + \beta) \\ \sin(\theta_X + \beta) \\ 0 \end{bmatrix} \quad (4-9)$$

4.3.2. Phase 2: Separation Axes Theorem (SAT) for Formulation of CAL Time Profile

As the flight conflict shape movement profile varies in orientation and heading at a point in time, their degree of interaction between the two aircraft is likened to the amount of intersection between two simple 3D convex moving objects. The well-known "Bentley-Ottmann Algorithm" [116, 117], which computes the intersection of objects from a set of input segments is commonly used to obtain a set of intersections. However, this approach can only determine the amount of intersection between two objects at only one instant. If it is to be evaluated across time, many iterations would then be needed making the approach cumbersome, slow and ineffective. Hence, a new approach is required which could determine accurately and quickly the level of intersection across time between two aircrafts.

The proposed CAL-SAT approach employs the ‘Separating Axes Theorem (SAT)’ or the ‘Hyperplane Separation Theorem’ [118, 119] used to evaluate the time intervals of intersection and full intersection of two 3D convex polygons. It states that “if two disjoint convex sets in n-dimensional Euclidean space sets are closed and at least one of them is compact, then there is a hyperplane exists between them.” When translated, this meant that “if two convex objects do not intersect, there exists an axis for which the projection of the objects will not overlap” [119]. The SAT concept has been applied successfully in computer graphics [120-123] to ascertain the degree and occurrence of intersection between a pair of 3D objects.

As such, an attempt is made to apply SAT to determine the 3D CAL time profile between two aircraft. To represent this theorem mathematically, let C_j be a set of convex polygons with different vertices $C_j \in \{V_i^{(j)}\} c_{i=0}^{N_j-1}$ and line L_j is a line

containing the projection of C in the unit direction vector $\vec{D}$. For moving object, the vertices $V_i^{(j)}$ can be represented as a function of time, t and L_j can be represented by equation (4-10).

$$L_j = [\lambda_{min}(\vec{D}), \lambda_{max}(\vec{D})] = [\min\{\vec{D} \cdot V_i^{(j)}\}, \max\{\vec{D} \cdot V_i^{(j)}\}] \quad (4-10)$$

where $V_i^{(j)} = f(t)$

For two convex objects C_0 and C_1 , where C_1 is longer than C_0 , the conditions on intersection and full intersection are given by (4-11) and (4-12) respectively. The corresponding timestamps when such conditions occur can then be deduced by solving for t .

$$\lambda_{min}^{(0)}(\vec{D}) \leq \lambda_{max}^{(1)}(\vec{D}) \text{ and } \lambda_{max}^{(0)}(\vec{D}) \geq \lambda_{min}^{(1)}(\vec{D}) \quad (4-11)$$

$$\lambda_{min}^{(0)}(\vec{D}) \geq \lambda_{min}^{(1)}(\vec{D}) \text{ and } \lambda_{max}^{(0)}(\vec{D}) \leq \lambda_{max}^{(1)}(\vec{D}) \quad (4-12)$$

For a flat plane, the convex object is a 2D polygon and the set of direction vectors to be used for projecting an object onto a line consists of its edge normal, as seen in (4-13). This projection method has been successfully used to identify extreme cases of intersection like edge-edge contact, vertex-edge contact and vertex-vertex contact. In addition, if one of the polygons is a circle, one needs to check for the direction vector that is the line joining the vertex of another object nearest to its centre [119].

In 3D space, to perform an intersection check between two 3D convex polygons, the normal vectors to the face of the polygon will first be used as direction vectors for projection. If there are any normal vectors that separate the planes, it indicates that no intersection occurs. Otherwise, the polygons are either coplanar or they are not parallel and split by the plane of the other polygon. If the polygons are coplanar, the potential separating direction vectors are those in the common plane, which are perpendicular to the edges, given by (4-14). Subsequently, if the polygons are not

parallel and divided by the plane of the other polygon, the potential separating direction vectors are those perpendicular to the touching edges, given by (4-15).

$$\vec{D} = (\vec{E}_i^j)^\perp \quad (4-13)$$

$$\vec{D} = \vec{N}^j \times \vec{E}_i^j \quad (4-14)$$

$$\vec{D} = \vec{E}_i^{(0)} \times \vec{E}_j^{(1)} \quad (4-15)$$

Where $\vec{E}_i^j$ is the edge vector joined by any two vertices and $\vec{N}^j$ is the normal vector to that plane. By applying SAT theorem and equations (4-10) to (4-15) where appropriate, one can then evaluate the flight conflict shape movement profile of 2 aircraft across time.

4.3.3. Phase 3: CAL Computation Between Aircraft Pair

This section outlines the methodology of how CAL value across time of two aircrafts is evaluated via the application of the SAT theorem as discussed earlier. From (4-4) to (4-9), it is observed that the height of the 3D moving convex object of any aircraft is invariant with time, t , as $CurrentFL_X, ClearedFL_X$ remain constant. Figure 4.8 shows the simplification of the 3D Aircraft Shape Movement into its vertical and lateral components. CAL evaluation via SAT theorem is first performed by applying a direct vertical level and lateral level computations separately on the two aircraft simultaneously. From the two sets of results derived, these are then used to determine the overall CAL value. In addition, the CAL profile inputs for two aircraft, X and Y, can be represented in equation (4-16), where t represents the elapsed time of both aircraft from the same reference starting time.

$$\begin{aligned} &CAL_{time} \text{ Profile} \quad (4-16) \\ &= f(P_X, P_Y, V_X, V_Y, HDG_X, HDG_Y, CurrentFL_X, ClearedFL_Y, \dots \\ &\quad CurrentFL_X, ClearedFL_Y, t) \end{aligned}$$

Figure 4.8. Simplification of 3D Aircraft Shape Movement into 2 components

4.3.3.1. Vertical CAL Computation

For the direct vertical level computation, the direction vector is to project the vertical heights of aircraft X and Y along the vertical axis, as illustrated in Figure 4.9. Using (4-11) and (4-12), one can determine via its projection whether there is any intersection between the two 3D moving convex objects vertically. A flowchart depicting how the vertical CAL score (CAL_{vert}) is computed is shown in Figure 4.10. From (4-11), it is observed that no intersection between aircraft X and Y exist in the vertical axis/plane. A $CAL_{\text{vert}} = 1$ is hence assigned. If a vertical level of intersection is observed when applying (4-11), (4-12) is then applied to determine whether the intersection is partial or full. If (4-12) is not met, $CAL_{\text{vert}} = 2$ is assigned indicating a partial intersection exists between aircraft X and Y vertically. If (4-12) is met, $CAL_{\text{vert}} = 3$ is given indicating a full vertical intersect occurs between aircraft X and

Y. It is also important to note that as vertical levels of the aircraft X and Y are invariant of time, the CAL_{vert} score is constant across the elapsed time t .

Figure 4.9. Projection of Vertical levels of Aircraft X and Y along the vertical axis

Figure 4.10. Process of Obtaining Vertical CAL score

4.3.3.2. Lateral CAL Computation

For the lateral level computation, the set of direction vectors $\vec{D}$, is used to perform SAT. $\vec{D}$ consists of a set of edge normal of aircraft pair X and Y, $\vec{N}_X, \vec{N}_Y$ and also a vector formed using the shortest line joining the vertex of one 2D moving convex object to another's centre, $(\vec{D}_{vertexcentre})_{shortest}$. Figure 4.11 depicts an illustration of aircraft pair X and Y and the set of direction vectors $\vec{D}$, which consists of $\vec{N}_X, \vec{N}_Y$, where $\vec{N}_X, \vec{N}_Y = \langle \vec{N}_{X12}, \vec{N}_{X13}, \vec{N}_{Y12}, \vec{N}_{Y13} \rangle$ and $(\vec{D}_{vertexcentre})_{shortest}$.

Figure 4.11. Illustration of a set of Direction Vector for Aircraft X and Y

Equation (4-17) shows how one such direction vector $\vec{N}_{X12}$, an edge normal of vertices 1 and 2 of aircraft X, can be calculated, while equation (4-18) shows how the shortest line joining the vertex of another 2D moving convex object nearest to its centre is calculated. It is found that shortest line joining the vertex of one aircraft to another's centre, is the vertex 2 of aircraft X and the centre of aircraft Y. Equation (4-17) can then be repeated for other vertices and $\vec{D}$ is successfully derived, where $\vec{D} = \langle \vec{N}_{X12}, \vec{N}_{X13}, \vec{N}_{Y12}, \vec{N}_{Y13}, \vec{D}_{X1Y1} \rangle$.

$$\overrightarrow{N_{X12}} = (P_{X2} - P_{X1})^\perp \quad (4-17)$$

$$\begin{aligned} (\overrightarrow{D_{vertexcentre}})_{shortest} &= \min\{\overrightarrow{D_{X1Y1}}, \overrightarrow{D_{X2Y1}}, \overrightarrow{D_{X3Y1}}, \overrightarrow{D_{X1Y2}}, \overrightarrow{D_{X1Y3}}\} \\ &= \overrightarrow{D_{X2Y1}} \end{aligned} \quad (4-18)$$

Using one of the direction vectors $\overrightarrow{N_{X12}}$ as an example, equation (4-10) is applied to the vertices C_X, C_Y , with projections along $\overrightarrow{N_{X12}}$, as seen in Figure 4.12.

Figure 4.12. Projection of Lateral Levels of Aircraft X and Y along one direction vector (edge normal)

In Figure 4.12, after aircraft X and Y are projected along one of the direction vector, $\overrightarrow{N_{X12}}$, where equation (4-11) and (4-12) are applied directly to determine the type of overlap present. In addition, the timestamps of where the CAL_{horz} score changes, are also computed accordingly. A flowchart of how (4-11) and (4-12) can be applied to determine the different lateral CAL score (CAL_{horz}) and its corresponding

timestamps is seen in Figure 4.13. Using $\overrightarrow{N_{X12}}$ as an example, (4-11) is first applied to determine the type of overlap present. If (4-11) is not fulfilled, it means that there is no intersection between aircraft X and Y laterally and $CAL_{horz} = 1$. If (4-11) is fulfilled, an intersection exists between aircraft X and Y along the projected direction vector, and its corresponding timestamps where (4-11) is calculated. These timestamps would represent the instances when the lateral overlap start and cease to exist, which correspond to the instances when CAL_{horz} would change from 1 to 2 ($t_{CAL\ 1\ to\ 2}$) and 2 to 1 ($t_{CAL\ 2\ to\ 1}$). Subsequently, (4-12) is applied to check for the type of intersection, if (4-11) is fulfilled. If (4-12) is not met, it meant that only a partial intersection exists between aircraft X and Y along the projected direction vector, hence, $CAL_{horz} = 2$. If (4-12) is met, a full intersection exists and $CAL_{horz} = 3$. As a result, the respective timestamps when the full intersection starts, and ends can be calculated, corresponding to the instances CAL_{horz} would change from 2 to 3 ($t_{CAL\ 2\ to\ 3}$) and 3 to 2 ($t_{CAL\ 3\ to\ 2}$). This process is then repeated for the other direction vectors $\vec{D}$ to derive a full set of CAL_{horz} score for each direction vector and its respective timestamps.

Figure 4.13. Process of Obtaining Lateral CAL score and its corresponding timestamps

4.3.4. Phase 4: Generation of CAL Time Profile

Upon evaluating both CAL_{vert} and CAL_{horz} , the overall CAL score ($CAL_{overall}$) is to be obtained, as summarised in Table 4.7. A full tabulated set of $CAL_{overall}$ score and its respective timestamps for every direction vector $\vec{D}$ is also obtained. As the CAL time profile curve represents how $CAL_{overall}$ changes with time for the two aircraft as a whole, an effective $CAL_{overall}$ score and the effective timestamps, $t_{CAL\ 1\ to\ 2}$, $t_{CAL\ 2\ to\ 1}$, $t_{CAL\ 2\ to\ 3}$, $t_{CAL\ 3\ to\ 2}$, for the intersection of the two objects would need to be generated. This is done by considering the different intersections along all the direction vectors of $\vec{D}$.

Table 4.7. Overall CAL Score Table

CAL	CAL _{vert} = 1	CAL _{vert} = 2	CAL _{vert} = 3
CAL _{horz} = 1	1	1	1
CAL _{horz} = 2	1	2	2
CAL _{horz} = 3	1	2	3

To illustrate, for two 3D CAL shape profiles to be considered as overlapping, an intersection must occur along all direction vectors. If an intersection does not exist in just one of the directional vectors, the two 3D CAL shape profile are not considered to be overlapping. Hence, the $(\text{CAL}_{\text{overall}})_{\text{effective}}$ score can be deduced by taking the minimum of the $\text{CAL}_{\text{overall}}$ score along all direction vector, $\vec{D}$. On the effective timestamps, $(t_{\text{CAL } 1 \text{ to } 2})_{\text{effective}}$ and $(t_{\text{CAL } 2 \text{ to } 1})_{\text{effective}}$ exist when $(\text{CAL}_{\text{overall}})_{\text{effective}} = 2$, while $(t_{\text{CAL } 2 \text{ to } 3})_{\text{effective}}$ and $(t_{\text{CAL } 3 \text{ to } 2})_{\text{effective}}$ exist when $(\text{CAL}_{\text{overall}})_{\text{effective}} = 3$. To deduce $(t_{\text{CAL } 1 \text{ to } 2})_{\text{effective}}$ and $(t_{\text{CAL } 2 \text{ to } 3})_{\text{effective}}$, the latest timestamp of the full set of $t_{\text{CAL } 1 \text{ to } 2}$ and $t_{\text{CAL } 2 \text{ to } 3}$ is used, as an overlap and full overlap between the two 3D CAL shape profiles only starts when such conditions are fulfilled on the last direction vector. Hence, this corresponds to the maximum $t_{\text{CAL } 1 \text{ to } 2}$ and $t_{\text{CAL } 2 \text{ to } 3}$ timestamps. On the contrary, for $(t_{\text{CAL } 2 \text{ to } 1})_{\text{effective}}$ and $(t_{\text{CAL } 3 \text{ to } 2})_{\text{effective}}$, the earliest timestamp of the full set of $t_{\text{CAL } 2 \text{ to } 1}$ and $t_{\text{CAL } 3 \text{ to } 2}$ is taken, as an overlap and full overlap between the two 3D CAL shape profiles stops on the earliest direction vector. In addition, as $t > 0$ (elapsed time), only positive values of the timestamps are valid and the CAL time profile and its $\text{CAL}_{\text{overall}}$ score starts from the corresponding instant, where $t > 0$. Equations (4-19) to (4-23) represents how the $(\text{CAL}_{\text{overall}})_{\text{effective}}$ score and the effective timestamps, $(t_{\text{CAL } 1 \text{ to } 2})_{\text{effective}}$, $(t_{\text{CAL } 2 \text{ to } 1})_{\text{effective}}$, $(t_{\text{CAL } 2 \text{ to } 3})_{\text{effective}}$, $(t_{\text{CAL } 3 \text{ to } 2})_{\text{effective}}$ can be computed.

$$(\text{CAL}_{\text{overall}})_{\text{effective}} = \min [(\text{CAL}_{\text{overall}})^{\vec{D}}] \quad (4-19)$$

$$(t_{\text{CAL } 1 \text{ to } 2})_{\text{effective}} = \max \left[(t_{\text{CAL } 1 \text{ to } 2} > 0)^{\vec{D}} \right] \quad (4-20)$$

where $(\text{CAL}_{\text{overall}})_{\text{effective}} = 2$

$$(t_{\text{CAL } 2 \text{ to } 1})_{\text{effective}} = \max \left[(t_{\text{CAL } 2 \text{ to } 1} > 0)^{\vec{D}} \right] \quad (4-21)$$

where $(\text{CAL}_{\text{overall}})_{\text{effective}} = 2$

$$(t_{\text{CAL } 2 \text{ to } 3})_{\text{effective}} = \min \left[(t_{\text{CAL } 2 \text{ to } 3} > 0)^{\vec{D}} \right] \quad (4-22)$$

where $(\text{CAL}_{\text{overall}})_{\text{effective}} = 3$

$$(t_{\text{CAL } 3 \text{ to } 2})_{\text{effective}} = \min \left[(t_{\text{CAL } 3 \text{ to } 2} > 0)^{\vec{D}} \right] \quad (4-23)$$

where $(\text{CAL}_{\text{overall}})_{\text{effective}} = 3$

As a result, the degree of intersection of 3D CAL shape profiles of aircraft X and Y, with respect to each other flying in an airspace across time on the radar screen can be captured and represented. The resulting CAL time profile curve between aircraft X and Y is thus obtained and shown in Figure 4.14, if $(\text{CAL}_{\text{overall}})_{\text{effective}} = 3$.

Upon establishing this, the CAL-SAT model is then compared with other complexity models. The CAL-SAT model is illustrated by calculating the instantaneous CAL score for the overall radar screen and regionally, before calculating the CAL time profile of some examples of flight configuration.

Figure 4.14. Illustration of CAL Time Profile Curve with the respective Timestamps

4.3.5. Application of CAL-SAT Model

To illustrate the proposed CAL-SAT model, it is applied to two common ATC traffic situations namely two aircraft cruising on the same airway and two aircraft flying past a crossing point in the airspace. These two ATC traffic situations serve as examples to showcase the difference in tactical complexity level projected in time requiring different tactical control strategies to be used. A standard 2K radar display highlighting an upper airspace (area control) sector was used to simulate these two case studies so as to demonstrate the different CAL time profiles (tactical complexity level) of aircraft pair.

4.3.5.1. Example 1: Two Aircraft Cruising on the Same Airway

Aircraft cruising on the same airway is a common ATC situation which ATCOs deal with regularly. The CAL-SAT model is applied to such situations in order to project the different levels of tactical complexity ahead of time, by providing the CAL time profile between aircraft pair.

Two different aircraft pairs cruising on the same airway were simulated. The first aircraft pair consists of Aircraft X and Y, while the second aircraft pair would be Aircraft Q and R. In both configurations, Aircraft X and Aircraft Q are behind

Aircraft Y and Aircraft R respectively. Aircraft X and Q are the faster aircraft. The speed of the slower Aircraft Y and R are also varied, where the speed of Aircraft R is 1.14 times faster than Aircraft Y. Their respective input parameters, which were flight information extracted directly from the radar screen, can be seen in Table 4.8, serving as the input into the CAL time profile, as described in equation (4-16).

Table 4.8. Initial Input Parameters for Example 1

Initial Parameters	Aircraft Position, (P_X, P_Y)	Speed (V), knots	Heading	Current FL	Cleared FL
Aircraft X	100, 1000	450	90	330	330
Aircraft Y	600, 1000	315	90	330	330
Aircraft Q	100, 1000	450	90	330	330
Aircraft R	600, 1000	360	90	330	330

Using these input parameters, the CAL-SAT model is able to predict that a full overlap exists both vertically and laterally, having a peak score of $(CAL_{overall})_{effective} = 3$, for both aircraft pairs, X and Y, Q and R respectively. Table 4.9 shows the $(CAL_{overall})_{effective}$ scores and the respective timestamps, $(t_{CAL\ 1\ to\ 2})_{effective}$, $(t_{CAL\ 2\ to\ 1})_{effective}$, $(t_{CAL\ 2\ to\ 3})_{effective}$, $(t_{CAL\ 3\ to\ 2})_{effective}$. The CAL time profile curves between aircraft X and Y, aircraft Q and R are shown in Figure 4.15.

From Figure 4.15, it is observed that for aircraft pair X and Y, the duration when $CAL_{overall} \geq 2$ is 227 seconds inclusive of 40 seconds when $CAL_{overall} = 3$. From the CAL time profile, based on present time, $t = 0s$, the ATCO is expected to experience a higher tactical complexity level of $CAL_{overall} = 2$ from 33 seconds onwards. This would last for 94 seconds after which the complexity level would further increase to $CAL_{overall} = 3$, which is of the highest tactical complexity level.

Table 4.9. Effective CAL overall score and timestamps for Example 1

CAL Time Profile Values	Aircraft X and Y	Aircraft Q and R
$(\text{CAL}_{\text{overall}})_{\text{effective}}$	3	3
$(t_{\text{CAL } 1 \text{ to } 2})_{\text{effective}}$	33	50
$(t_{\text{CAL } 2 \text{ to } 3})_{\text{effective}}$	127	210
$(t_{\text{CAL } 3 \text{ to } 2})_{\text{effective}}$	167	250
$(t_{\text{CAL } 2 \text{ to } 1})_{\text{effective}}$	260	410

Figure 4.15. Illustration of CAL Time Profile Curve for Aircraft X and Y, Aircraft Q and R

For aircraft Q and R, duration when $\text{CAL}_{\text{overall}} \geq 2$ is 360 seconds inclusive of 40 seconds when $\text{CAL}_{\text{overall}} = 3$. In this case, the higher tactical complexity level, $\text{CAL}_{\text{overall}} = 2$ would occur from 50 seconds onwards, lasting for 160 seconds before the highest tactical complexity level, $\text{CAL}_{\text{overall}} = 3$ occurs. This is owing to the 3D CAL shape profile of the back aircraft Q, taking a longer time to start overlapping and eventually overtaking Aircraft R as compared to Aircraft X on Aircraft Y. This

arises as there is a reduction of absolute speed difference seen in aircraft Q and R, as opposed to aircraft X and Y. It is also noted that the duration of $CAL_{overall} = 3$ for both aircraft pairing is constant, at 40 seconds. This indicates that the difference in speeds of the slower aircraft in the aircraft pairs under this 3D CAL profile configuration does not significantly affect the duration of highest complexity.

From the above results, two observations can be made. Firstly, the profile curves provide a projected time buffer ahead before a higher tactical complexity level, $CAL_{overall} = 2$ is encountered. It also highlights that Aircraft pair Q and R have 17 seconds longer time buffer than Aircraft pair X and Y. If left unattended, both aircraft pairs' 3D CAL shape profile are expected to fully overlap with each other. Second, one can infer if an ATCO needs more time before one starts to deal with tactical complexity issues, a control strategy to adopt is to increase the speed of the front aircraft or decrease the cruising speed of the back aircraft on an airway. Conversely, one could also vary the relative speeds in the Aircraft pair to lower the tactical complexity level.

4.3.5.2. Example 2: Two Aircraft Flying Past a Crossing Point

Another common ATC situation is that of two aircraft flying past a crossing point. Similarly, the CAL-SAT model is applied to two different aircraft pairs to ascertain the different levels of tactical complexity ahead of time between aircraft pairings.

Table 4.10 shows the sets of input parameters for two Aircraft crossing pairs, A and B, and C and D. Their flight information can be extracted directly from the radar screen. The aircraft pair are expected to fly past a fixed crossing point where its airways are at an angle of 90° . For the crossing pair of Aircraft A and B, they were to cross a fixed waypoint at the same instant, whereas Aircraft D flew across this fixed waypoint 60 seconds ahead of Aircraft C.

Table 4.10. Initial Parameters for Example 2

Initial Parameters	Aircraft Position, (P_X, P_Y)	Speed (V), knots	Heading	Current FL	Cleared FL
Aircraft A	2600,3000	450	180	330	330
Aircraft B	100,1000	360	90	330	330
Aircraft C	2600,3480	450	180	330	330
Aircraft D	100,1000	360	90	330	330

From these input parameters in Table 4.10, their CAL time profiles are to be generated. It can be seen that only a partial overlap exists laterally between these two aircraft having a peak score of $(\text{CAL}_{\text{overall}})_{\text{effective}} = 2$. No time duration was given at $(t_{\text{CAL } 2 \text{ to } 3})_{\text{effective}}$, $(t_{\text{CAL } 3 \text{ to } 2})_{\text{effective}}$ as the highest level of complexity was not reached and the respective timestamps for $(t_{\text{CAL } 1 \text{ to } 2})_{\text{effective}}$, $(t_{\text{CAL } 2 \text{ to } 1})_{\text{effective}}$ were seen in Table 4.11. Figure 4.16 shows the CAL time profile curves between aircraft A and B, C and D.

Table 4.11. Effective CAL overall score and timestamps for Example 2

CAL Time Profile Values	Aircraft A and B	Aircraft C and D
$(\text{CAL}_{\text{overall}})_{\text{effective}}$	2	2
$(t_{\text{CAL } 1 \text{ to } 2})_{\text{effective}}$	206	273
$(t_{\text{CAL } 2 \text{ to } 3})_{\text{effective}}$	-	-
$(t_{\text{CAL } 3 \text{ to } 2})_{\text{effective}}$	-	-
$(t_{\text{CAL } 2 \text{ to } 1})_{\text{effective}}$	250	304

Figure 4.16. Illustration of CAL Time Profile Curve for Aircraft A and B, Aircraft C and D

From Figure 4.16, it is observed that the duration when $CAL_{overall} = 2$, for aircraft A and B, C and D are 44 and 31 seconds respectively. Such differences arise as meeting at the same waypoint (crossing point) at the same instance for Aircraft A and B meant a larger degree of overlap between their respective 3D CAL shape profile exists. In addition, from the CAL time profile of Aircraft A and B, based on present time, $t = 0s$, the ATCO is expected to experience a high tactical complexity level of $CAL_{overall} = 2$ from 206 seconds onwards, whereas a high tactical complexity level of $CAL_{overall} = 2$ is expected only after 273 seconds onwards for Aircraft C and D. This occur when Aircraft C, the aircraft further as well as takes a longer time to reach the crossing point, overlaps the 3D CAL shape profile of Aircraft D. The results highlight that two aircraft flying past a crossing point with a time difference would result in a later occurrence of high complexity, $CAL_{overall} = 2$, and a shorter duration of high complexity. To moderate the high tactical complexity of the airspace situation, one tactical control strategy could be to consider vectoring the aircraft to fly a longer distance, so that there is a time delay between the other aircraft flying past the crossing point. This could in turn delay the occurrence of higher complexity and reduce the duration of higher complexity for the crossing pair.

With the new CAL time profile, the exact duration in which a higher complexity will last is known. As a result, an objective method of providing tactical manoeuvre from a pairwise complexity time profile, which was not present in current methods, is enabled.

4.4. Summary of Findings

In this chapter, a new tactical complexity calculation method, CAL, for an instantaneous overall and regional score, based on user specified input location and time, has been presented. CAL can determine the level of complexity pending on the state of overlap from the spatial shapes of individual aircraft defined in the airspace, in the various user specified region for every radar frame update, which is 9.8 seconds in this case.

For instantaneous CAL, calculation can be performed at every time frame, thus allowing any slight deviation or change to be tracked more accurately. A trend analysis of complexity can also be performed with historical data, to track the periods of high and low complexity. Hence, any sudden changes in complexity can be identified and isolated for further analysis of the exogenous traffic movements.

Test validation of CAL analysed at factor level indicates that the proposed CAL model is consistent with other established complexity models. At model level, validation of CAL with Delahaye's complexity model for the complexity score highlights that both models produce the same complexity ranking order over a range of air traffic scenarios.

Hence, the proposed approach (CAL) is able to perform real time dynamic traffic complexity evaluation which could serve as a useful planning tool in allocation and duration of shift duties to ATCOs. Risk assessment and analysis in designated spatial areas can also be performed as well as to identify regions of high traffic complexity. Nevertheless, the proposed method may be constrained by the number of aircraft within a particular ROI. This may make it difficult for ATCOs to define the exact ROI for complexity evaluation particularly if one is dealing with an unfamiliar airspace sector for the first time. This challenge can, however, be mitigated through experience in consultation with more senior ATCOs.

For the calculation of the CAL time profile between aircraft pair based on current instantaneous aircraft parameters, the CAL-SAT model has also been successfully developed. This model accounts for the dynamic traffic flow characteristics of the aircraft and its network characteristics, while allowing tactical complexity to be projected across time. This allows the pairwise air traffic flow to be modelled and a tactical complexity analysis of the air transportation network to be established.

The proposed CAL-SAT model was applied on two common ATC examples. Variations in the CAL time profiles were observed, and they could aid ATCOs in adopting appropriate tactical control strategies to minimise tactical complexity within that section of the airspace. The suggested strategies could involve altering the speed difference between the two aircraft cruising on an airway, vectoring an aircraft to fly a longer distance in a crossing situation, so that the high complexity level would be delayed or moderated accordingly. Such strategies can enable ATCOs more time to handle other pressing issues should the need arise.

Through the CAL time profile between aircraft pairs, the different tactical complexity levels and their predicted time occurrences, the model enhances greater time predictability with respect to tactical complexity level and identification of critical time buffer zones between aircraft pair. This would facilitate greater awareness of ATCOs in terms of task prioritisation especially in heavy traffic situations, adopt appropriate tactical control strategies and better manage the amount of time required to react before the situation gets more critical. As a result, these measures can serve to aid ATCOs tactically in their tasks, together with the different tactical control strategies adopted. In addition, an objective method to derive the various tactical control strategies, depending on the CAL time profile is enabled.

The model can also pave the way for a useful planning tool to be developed, assisting watch managers in the allocation and duration of shift duties assigned to respective ATCOs. Airspace designers could also benefit by considering the effects of tactical complexity while designing the airspace.

5. Chapter 5 Perception and Comprehension of ATCO in their Tactical Monitoring Activity

This chapter proposes new measurement techniques that seek to fulfil all seven desired criteria described in section 2.3.4, which are namely, the use of eye tracking technique, being consistent and not subjected to bias, accurately detect and identify changes, non-disruptive, covers the full ATC spectrum, non-intrusive and continuous across time, to extract and represent knowledge of an ATCO's perception and comprehension level in their tactical monitoring activity. As eye tracking technique is the most direct form of measurement of an ATCO's visual monitoring activity, this chapter focuses on using eye tracking technique as the primary measurement.

5.1. Physiological Signals of ATCO in Area Control

In order to capture and evaluate the perception and comprehension of ATCOs, there is a need to identify the different physiological signals exhibited by them during their tactical control activity.

For an ATCO operating in radar surveillance, physiological signals exhibited directly by ATCOs in their task include their eye and hand movement for looking visually on the radar screen and interacting with the ATC interface. Measurement techniques proposed in this research will involve eye tracking technique and Human Machine Interface (HMI) inputs as an additional secondary signal, as it presents an extra understanding of an ATCO's perception and comprehension level. Hence, the proposed measurement techniques seek to establish and use signature metrics from an ATCO's eye movement and HMI inputs on the area control ATC workstation and interface.

5.2. Description of ATCO activity management

According to a Eurocontrol study, activities that require ATCOs' management, which are still relevant in their future role are, aircraft flying in crossing (potential conflict), aircraft frequency switch and the general flight path monitoring of aircraft [18]. To manage these events in an active and disciplined manner, ATCOs are required to look at the different aircraft on the radar screen deliberately [10, 124].

Hence, these activities are studied in deeper detail to establish the signature metrics of ATCOs. Table 5.1 provides a summary of such activities and describes their characteristics accordingly.

Table 5.1. ATCO Activity Management and their characteristics

ATCO Management	Activity	Characteristics of Activity
Aircraft in potential conflict (crossing): 1. Aircraft in crossing (crossing monitoring)		<ul style="list-style-type: none"> • 2 aircraft are placed in potential conflict • They are flying towards the possible fixed point, from a certain distance away • Distance between the aircraft is reducing as time passes by • Vertical profile of the 2 aircraft overlaps, causing a potential conflict
Aircraft frequency switch 1. For incoming aircraft, taking jurisdiction of it 2. For outbound aircraft, handing over of it		<ol style="list-style-type: none"> 1. For incoming aircraft, as it approaches the sector boundary, pilot to call into ATCO's frequency, so that ATCO can take jurisdiction of it 2. For outbound aircraft, as it approaches the sector boundary, ATCO would have to hand it over to the adjacent sector
Generic flight path monitoring 1. Change FL flight 2. Cruising flight		<ul style="list-style-type: none"> • Aircraft are flying along the designated airway in the ATCO's sector of control • Aircraft will fly along this airway from the acceptance to handing over

As a result, there is a need to identify and formulate signatures using both eye and hand movement for each of these activities, by mapping the activities' characteristics to an ATCO behaviour. This work tries to identify the different aspect in which an ATCO would perceive and comprehend such activities, by mapping it to

characteristics of these activities. From these signatures, new eye metrics can be derived to evaluate the perception and comprehension level of ATCOs in the different monitoring activities.

5.3. Experimental Setup

5.3.1. Experimental Sessions

In this chapter, 88 one-hour experimental sessions of data were collected among male participants whose ages varied between 24 and 41 ($M = 29$, $SD = 5.34$). These sessions comprised 24 novice sessions (zero ATC experience, only ATC knowledge), 20 intermediate sessions (more than 50 hours of simulator ATC training and ATC knowledge, yet to handle live traffic) and 44 expert sessions (licensed ATCOs with more than three months of live traffic experience) [125].

Prior to conducting the experiments, a power analysis in repeated-measure design, is conducted, to determine if the number of experimental sessions were sufficient [126, 127]. For studies involving human participants in ATC, an 80% statistical power with $\alpha = 0.05$ is required [128, 129]. To compute the statistical power, the effect size was calculated to be 0.350, the minimum correlation is found to be 0.3 and the number of levels is 3, for three different expertise group. Using these values, the minimum number of sessions required for each expertise group is found to be 18 for a statistical power of 80%. In addition, the 88 one-hour experimental sessions of data collected is also found to be more than the number of sessions among the different eye tracking studies of ATCO, which is between 22 to 72 experimental sessions [59, 62, 63, 65, 93, 94, 130].

5.3.2. Experimental Setup

For the experiment, a real-time simulator, the NLR ATM Research SIMulator (NARSIM), was used to generate and simulate air traffic scenarios in real time, with every radar update at 9.8 seconds. Pseudo-pilots were used to facilitate the flying of aircraft, by following the same scenario script, so that events in the same scenario occurred at the same instant. A standard Controller Working Position (CWP), consisting of a 2K radar screen (50cm by 50cm, equivalent to 20 inches by 20 inches) was used to display air traffic data in a given airspace sector, as seen in Figure 5.1.

Figure 5.1. A Standard Controller Working Position (CWP) with remote eye tracker

A remote eye tracker, Tobii X2-30 was used to capture the eye data of the participants in a non-intrusive manner. Under ideal conditions, its accuracy and precision are 0.4° and 0.26° respectively [131]. In this setup, the eye tracker is positioned 18 cm in front of the screen, 55cm from the participant's eye, to extend the eye tracker's field of view so that gaze data on any regions of the 2K screen can be captured. This meant that the eye tracker is deployed in a non-ideal condition that closely mimic the ATCOs' working environment. Hence, a study was conducted to determine the accuracy and precision of the eye tracker without a chinrest, prior to this study, for this non-ideal condition [101, 132, 133]. For a total of 3128 gaze data samples, the accuracy and precision of the Tobii X2-30 was found to be 3.5° and 1.1° respectively, with good validity of 93.7%. These values of accuracy and precision of the Tobii X2-30 is quite close to that reported by Clemotte et. al [101], which is 2.5° and 2.0° respectively, performed using the same eye tracker model under non-ideal conditions.

Raw eyeball movement and radar data are extracted from the Tobii eye tracker and NARSIM respectively via an intelligent real-time post processing server, using the "Dynamic Data Alignment and Timestamp Model" that has been presented in Chapter 3. This ensures that the two data streams are synchronous in time and space. The two sets of extracted data are then computed to determine the various eye tracking metrics. Using these accuracy and precision values, the velocity threshold in the I-VT algorithm for fixation determination is $105^\circ/\text{s}$ [105], and the new boundaries of the aircraft's track and label for the mapping of a fixation would be a 70 pixel

diameter and 230 pixel diameter circle, respectively. The metrics data were then relayed to the Thales TopSky-HF software to record the data of the different test participants [81, 113]. Therefore, the eye metrics used for the signature identification were already mapped to a flight object on the radar screen, using the “Dynamic Data Alignment and Timestamp Model”. Detailed explanation of this eye metric derivation is explained in Chapter 3.

5.3.3. Experimental Procedure and Scenario Definition

Prior to the experiment, each participant involved in a session underwent an initial 9-point eye-tracker calibration exercise. Calibration was repeated until a satisfactory calibration was obtained that refers to Tobii Studio’s qualitative calibration report.

Real time simulations were conducted for 88 one-hour experimental sessions, with different scenarios consisting of 60 aircraft each, that mimic operational air traffic, which is approximately 1.2 times that of the regular traffic volume. The airspace of interest in this real time study was based on an existing airspace sector, with information referenced from the publicly available SkyVector website [134]. In this airspace sector, there are a total of 4 different merging points and 21 crossing points. There is a mixture of climbing and cruising flight along the different airways (flight path), and they also comprise both wide and medium angle crossing points, close and independent crossing points, as well as crossing points at the center or corner of the 2K radar display. In addition, the aircraft are also flying on 7 unidirectional airways and 3 bi-directional airways in this airspace sector. Such specifications meant that the scenario designed in this study were that of a very complex sector, as other studies involving real time simulations in the field of ATC usually uses airspace sector that comprise of less than 10 crossing points and aircraft at the regular traffic volume [59, 62, 63, 65, 93, 94, 130].

A wide angle crossing point is defined as a crossing point, with an angular difference of 45 to 180 degrees between the two intersecting airways, whereas a medium angle crossing point is one with an angular difference of 16 to 44 degrees between the two intersecting airways [114].

Close proximity crossing is defined as a crossing point with another one within 10 to 20 Nautical Miles (NM) from it and independent proximity crossing is defined as a

crossing point with another crossing point more than 20NM away from it. The value of 10NM is selected as it is the Required Navigation Performance (RNP) standard which all of the aircraft are to observe in which an aircraft should not deviate left and right by more than 10NM. Figure 5.2 provides a depiction of the close and independent crossing points.

Figure 5.2. Pictorial Illustration of Close and Independent Crossing Points

A crossing point located at the center and corner of the radar screen is defined based on their pixel coordinates. In this comparison, two wide angle crossing points are selected. Its coordinates (pixel location on 2K screen) are shown in Table 5.2, while Figure 5.3 shows a pictorial illustration of the location of these crossing points. Waypoint KILOT is circled red and located at the corner of the screen, while SUSAR, circled in yellow, is located at the centre of the screen, as seen in Figure 5.3.

Table 5.2. Pixel Coordinate of Selected Waypoints

Waypoint	Pixel X	Pixel Y
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KILOT	726	1576
SUSAR	1025	1099

Figure 5.3. Pictorial Illustration of Waypoints in the airspace

5.4. Activity Management 1 – Aircraft Crossing with Potential Conflict

Two approaches, crossing point envelope analysis and crossing monitoring identification, were explored to identify the signature of how an ATCO would perceive and comprehend for the activity of managing aircraft crossing with potential conflict. To do so, it is believed that an ATCO would fixate on the aircraft pair-in-crossing more often and for a longer duration, to identify them and understand their flight state before issuing the appropriate commands. A discussion of how these approaches fared are explained in the ensuing sections.

5.4.1. Approach 1: Crossing Point Envelope Analysis

A crossing point envelope analysis involving a general calculation of the mean fixation count and fixation duration for each aircraft pair-in-crossing was performed. A crossing point envelope depicts waypoint with up to 4 minute flight time from an aircraft's position. This crossing point envelope is chosen as twice that of the Short Term Conflict Alert (STCA), which is 2 minutes. Furthermore, this is also consistent with the study of Eyferth et. al, as they found that ATCOs start to detect a conflict 4 to 5min before it occurs [135]. This boundary is therefore used as the region in which test participants seek to detect and monitor aircraft pair-in-crossing.

The mean fixation count and fixation duration are found by taking the average of the total fixation count and fixation duration of all participants for each subject group for the respective aircraft pair-in-crossing. Hence, the mean fixation count and fixation duration plots for six randomly selected aircraft pairs-in-crossing are shown in Figure 5.4 respectively.

Figure 5.4. Comparison of mean fixation count and mean fixation duration for 6 selected aircraft pairs-in-crossing

From Figure 5.4, it is observed that the mean fixation count and duration are almost similar among the different expertise levels, except for selected aircraft pairs-in-crossing where the intermediate participants tend to exhibit more fixation count and duration. Hence, it can be established that using the general calculation of mean fixation count and duration in a crossing envelope is ineffective in distinguishing the monitoring behaviour for the different expertise levels. One reason for such finding

could be that ATCOs do not monitor for crossing during the entire duration along the airway up till the crossing point. Throughout the entire duration, there could only be a few instances where the fixations are meant for monitoring of crossing, while in the rest of the cases the ATCO is only monitoring for other purposes, like its generic flight path. This is also consistent with other research studies which use task-specific situations (i.e. information selection or memory processing) to differentiate the expertise levels of participants [136, 137]. Hence, the eye metrics required to differentiate the expertise levels needed to be further refined in order to filter instances where the ATCO is only monitoring for crossing.

5.4.2. Approach 2: Crossing Monitoring Identification

To fully represent the knowledge of an ATCO's perception and comprehension for aircraft pairs-in-crossing, several methods have been proposed by researchers. A popular method involves the use of identifying the instance where ATCOs compare the aircraft pairs-in-crossing consecutively to determine if they could cross each other in a potential conflict. Such is seen in the MTAHC algorithm by Kang et. al [59-61, 95] and the creation of single aircraft pair-in-crossing scenario by Marchitto et. al [63].

However, these algorithms were created when the participants were specifically tasked to only identify aircraft pairs-in-crossing, with some scenarios involving one aircraft pair. As such, participants are not required to multi-task and consider other factors in the full ATC tasks, which do not mimic the operational scenarios. Hence, in an operational ATC monitoring task, it is essential to identify the instances only when the ATCO perceives and comprehends the aircraft pairs-in-crossing, to build upon the method of ATCOs comparing these aircraft consecutively.

For the activity of aircraft crossing with potential conflict, to ascertain if two aircraft are in a conflict, an ATCO would have perceived and comprehended this by fixating on the aircraft pair-in-crossing more often and for a longer duration. Therefore, fixation count and duration are plotted against frame number for the aircraft pairs-in-crossing, and their corresponding peaks are observed at certain frames, indicating that the participant looks at the aircraft-of-interest more than average. The frame number refers to the number of frames elapsed since the start of the radar simulation with

each frame being 9.8 seconds and fixation peaks are defined as instances where fixation count or fixation duration is above the average number of non-zero fixation count or duration of an individual. Figure 5.5 shows a fixation count and duration plot across the elapsed frame number for the aircraft pair-in-crossing EVA780 and SIA692, using one participant from each of the participant groups (expert, intermediate and novice). EVA780 enters the radar screen at frame 75 while SIA692 enters the radar screen at frame 43, and they will cross at the same crossing point at frame 116.

Figure 5.5. Fixation Count and Duration plot of EVA780 and SIA691 across the elapsed time frame till crossing

Using the intermediate participant in Figure 5.5, the fixation count plot for EVA780 has its fixation peaks occurring around frames 102, 106 and 114. Likewise, in the fixation duration plot, fixation peaks are also occurring around frames 93, 102, 106 and 114. Similarly, for the fixation count plot of the other aircraft SIA692, there are fixation peaks at frames 54, 101, 106, 109 and 114 and there are fixation peaks at frames 90, 109 and 114 for the fixation duration plot. A similar plot was also made for aircraft pairs-in-crossing, AXM540 and TGW791, as seen in Figure 5.6 and similar observations showing the fixation peaks were made.

From these observations, it is found that fixation count and duration peaks are occurring at around the same time for both aircraft pairs-in-crossing. For EVA780 and SIA692, the aligned fixation peaks occurred at frames 101 to 102, 106, and 114,

while for AXM540 and TGW791, these aligned peaks were found at frames, 2, 4, 8 to 10, 13 to 14, 17 to 18, 22, 27, 31, 34 and 37. This indicates that aligned peaks only occurred as the aircraft pairs-in-crossing approaches the crossing point. In addition, the peaks of the aircraft which were not aligned could likely mean the participant monitoring it for other purposes, while those aligned likely showcased the intent of the participant in performing crossing monitoring. Therefore, fixation peaks and its alignment in time could be investigated further in relation to the crossing monitoring behaviour of participants for aircraft crossing with potential conflict.

Figure 5.6. Fixation Count and Duration plot of AXM540 and TGW971 across the elapsed time frame till crossing

By adopting this approach of fixation peaks for both count and duration, together with their alignment, an ATCO's deliberate monitoring of the selected aircraft pair-in-crossing is filtered. Furthermore, in the monitoring of aircraft crossing with potential conflict, ATCOs need to identify the 2 aircraft for crossing monitoring, before comparing between them within a short span of time. Hence, by adopting this approach, instances when ATCOs monitor to compare the 2 involved aircraft are also identified. This highlights the potential of using the approach of fixation count and duration peaks and their alignment in capturing and evaluating how ATCOs perceive and comprehend aircraft in their crossing monitoring activity, thereby describing their crossing monitoring signature.

5.4.3. Formulation of Crossing Monitoring Signature.

By using the fixation peaks and its alignment for aircraft pairs-in-crossing, a crossing monitoring signature can be formulated to capture and evaluate the perception and comprehension level of ATCO for aircraft crossing with potential conflict. This is a novel method to represent the crossing monitoring behaviour of ATCOs, as it can identify the instances where the ATCOs are monitoring for crossing, on specific aircraft callsigns. Figure 5.7 shows an overview of the formulation of this signature, which consists of three different phases.

Figure 5.7. Overview for the Formulation of Aligned Fixation Peaks Signature for Crossing Monitoring

5.4.3.1. Phase 1: Identification of Fixation Peaks

In phase 1 of the formulation of crossing monitoring signature, fixation peaks of the ATCO's monitoring of aircraft pairs-in-crossing are first identified. This is performed by plotting the fixation count and duration against frame number for the aircraft pairs-in-crossing, as seen previously in Figure 5.5 and Figure 5.6, for aircraft pair-in-crossing EVA780 and SIA692, AXM540 and TGW791 respectively. A fixation peak is then identified by instances where the fixation count or fixation duration is more than the average number of non-zero fixation count or duration exhibited by an ATCO across time.

5.4.3.2. Phase 2: Establishing the Alignment of Fixation Peaks

As there are fixation peaks occurring near to each other for the aircraft pairs-in-crossing, this could mean that the ATCO is monitoring the aircraft-of-interest more than usual within that duration. Hence, aligned fixation peaks could indicate the crossing monitoring behaviour of ATCOs, as they need to compare the aircraft pairs-in-crossing at around the same time, to be aware of its possible crossing occurring later. A tolerance of ± 1 frame is set for the interval of an aligned fixation peak, to consider cases in which the series of fixation is exhibited across a frame transition. Using the aircraft pair-in-crossing EVA780 and SIA692, Figure 5.8 provides an illustration of the different cases that are used to quantify an aligned fixation peak. A fixation is represented by a black square, while the aircraft's flight object on the radar screen, track and label, are represented using a circle and square respectively.

Figure 5.8. Illustration of Aligned Fixation Peak Definition and Tolerance

To ascertain that aligned fixation peaks describe the crossing monitoring behaviour of an ATCO, the number of aligned fixation peaks was measured for four cases– 1)

comparison between aircraft pair-in-crossing (crossing case), 2) comparison between aircraft-in-crossing with a nearby aircraft (non-crossing case), 3) comparison between aircraft-in-crossing with another random aircraft (non-crossing case) and lastly, 4) comparison between two non-crossing aircraft. A total of 3 crossing point instances, comprising of one crossing point instance per expertise group, were chosen in each of these comparisons. A brief explanation of the four cases as well as results of this investigation are also discussed and summarised.

Case 1: Comparison of aircraft pair-in-crossing (CSN387 & GIA275)

The crossing pair used for this case is CSN387 and GIA275 which will cross simultaneously at DUBSA at frame 156. CSN387 is flying on airway M771 and GIA275 is flying on airway L629, with a common time frame of 86 to 156. A pictorial illustration of the aircraft pair-in-crossing, CSN387 and GIA275, flying across DUBSA in crossing with potential conflict, at frame 98, is shown in Figure 5.9. The fixation count and duration plots across the elapsed time frame for CSN387 and GIA275, for one participant in each expertise group is shown in Figure 5.10.

From Figure 5.10, aligned fixation peaks for both fixation count and duration are observed. Expert participant exhibited aligned crossing monitoring thrice at frames 140, 141 and 149. Intermediate exhibited aligned crossing monitoring thrice at frames 139, 141 and 142, while the novice participant exhibited aligned crossing monitoring twice at frames 146 and 155. The total number of aligned peaks for every participant in this case were tabulated and shown in the summary of the four different cases.

Fixation Duration Heatmap of Frame 98, from 00:16:03.052 to 00:16:12.911

Figure 5.9. Pictorial Depiction of Case 1 Scenario, with aircraft pair-in-crossing CSN387 and GIA275 at frame 98

Figure 5.10. Fixation Count and Duration plot of CSN387 and GIA275 across the elapsed time frame till crossing

Case 2: Comparison of aircraft-in-crossing with nearby aircraft (SIA141 near aircraft pair-in-crossing CSN387 and GIA275)

In this case, the presence of aligned fixation peaks with an aircraft near the aircraft-pair-in-crossing is investigated. A comparison was made between SIA141 and the same aircraft pair-in-crossing in case 1, CSN387 and GIA275. SIA141 is also flying on M771, but started ahead of CSN387 at frame 77, as depicted in Figure 5.11.

Fixation Duration Heatmap of Frame 98, from 00:16:03.052 to 00:16:12.911

Figure 5.11. Pictorial depiction of Case 2 Scenario, with aircraft pair-in-crossing CSN387 and GIA275 at frame 98, with SIA141 as an aircraft nearby

The fixation count and duration plot for CSN387 and SIA141, GIA275 and SIA141 were investigated and illustrated in Figure 5.12 and Figure 5.13 respectively. It is observed from Figure 5.12 and Figure 5.13 that aligned fixation peaks are present in the plots, however, there seem to be lesser number of them as opposed to Case 1. The total number of aligned fixation peaks were also tabulated for aircraft pairs CSN387 and SIA141, GIA275 and SIA141. The presence of aligned fixation peaks between these different aircraft pair combinations could be due to the participant trying to identify the correct aircraft pair-in-crossing. Hence, these show that by identify the

right aircraft pair-in-crossing, a participant would have exhibited the aligned fixation peak signature.

Figure 5.12. Fixation Count and Duration plot of SIA141 and CSN387 across the elapsed time frame till crossing

Figure 5.13. Fixation Count and Duration plot of SIA141 and GIA275 across the elapsed time frame till crossing

Case 3: Comparison of aircraft-in-crossing with a random aircraft

In this case, a random aircraft which was present on the radar screen throughout the flight duration before the aircraft pair CSN387 and GIA275 crosses the crossing point, DUBSA, was selected. In this example, aircraft SIA371 flying on N891, which has

no influence on aircraft pairs CSN387 and GIA275, with start frame of 47 was chosen to be compared among them individually. A pictorial illustration of the aircraft pair-in-crossing, CSN387 and GIA275, together with an illustration of the position of SIA371 on the radar screen, at frame 98 is shown in Figure 5.14. The fixation count and duration plot for SIA371 and CSN387, SIA371 and GIA275 are given in Figure 5.15 and Figure 5.16 respectively. In this case, the number of aligned fixation peaks is observed to be much lesser than the earlier cases, and the corresponding total number of aligned fixation peaks were also tabulated and discussed in the ensuing sections. This mean that the participant is able to deduce that no potential conflict is present for the aircraft pairing of SIA371 and CSN387, SIA371 and GIA275, thereby resulting in the low number of aligned fixation peaks, as there is no need to monitoring for crossing with potential conflict. The number of aligned fixation peaks are tabulated and seen in the summary section.

Fixation Duration Heatmap of Frame 98, from 00:16:03.052 to 00:16:12.911

Figure 5.14. Pictorial depiction of Case 3 Scenario, with aircraft pair-in-crossing CSN387 and GIA275 at frame 98, with SIA371 as a random aircraft

Figure 5.15. Fixation Count and Duration plot of SIA371 and CSN387 across the elapsed time frame till crossing

Figure 5.16. Fixation Count and Duration plot of SIA371 and GIA275 across the elapsed time frame till crossing

Case 4: Comparison of two non-crossing aircraft

In this case, a comparison is made between MAS206 and EVA324, which are two non-crossing aircraft. MAS206 is flying on L629, starting at frame 162 and crossing at NOPAT at frame 244, whereas EVA324 is flying on L644, starting at frame 172 and crossing at OPULA at frame 220. Locations of the 2 aircrafts are seen in Figure 5.17 and the fixation peak plots for MAS206 and EVA324 is illustrated in Figure 5.18.

Fixation Duration Heatmap of Frame 181, from 00:29:39.670 to 00:29:49.538

Figure 5.17. Pictorial depiction of Case 4 Scenario, with two random aircraft MAS206 and EVA324 at frame 181

Figure 5.18. Fixation Count and Duration plot of MAS206 and EVA324 across the elapsed time frame till crossing

It is observed from Figure 5.18 that no alignment of fixation peaks is present for both the fixation count and fixation duration plots of MAS206 and EVA324. This shows that all participants are able to identify that these two aircraft will not cross based on

their respective trajectories, hence no aligned fixation peaks are observed. Similarly, the number of aligned fixation peaks are tabulated, which would be compared with the other earlier cases.

Summary of Findings for all cases

To summarise the total number of aligned fixation peaks were tabulated for all four cases for individual expertise group, as seen in Table 5.3.

Table 5.3. Comparison of Number of Aligned Peaks for different cases on all three expertise groups

	No. of Aligned Peaks (Expert)	No. of Aligned Peaks (Intermediate)	No. of Aligned Peaks (Novice)
(1) CSN387 & GIA275	3	3	2
(2a) SIA141 & CSN387	6	4	5
(2b) SIA141 & GIA275	2	1	1
(3a) SIA371 & CSN387	0	0	0
(3b) SIA371 & GIA275	0	0	0
(4) MAS206 & EVA324	0	0	0

From Table 5.3, aligned peaks are observed in cases (1) and (2) but not in cases (3a), (3b) and (4). This meant that when the aircraft have zero chances of crossing based on their respective trajectories (as depicted in case (3a), (3b) and (4)), participants of all expertise group do not have aligned fixation peaks, as they have noted that these aircraft have no relation with each other. As a result, the aligned fixation peaks signature is not present. It is therefore safe to conclude that there is strong relationship between the total number of aligned fixation peaks and crossing monitoring events, where participants need to ascertain that a crossing with potential conflict exist. This verifies the approach of using aligned fixation peaks to represent crossing monitoring events for aircraft pairs-in-crossing.

5.4.3.3. Evaluation of Aligned Fixation Peaks Signature

Upon establishing the aligned fixation peaks signature for crossing monitoring behaviour of ATCOs, four metrics (3 continuous and 1 boolean) were derived to describe each of these signatures. The three continuous metrics are namely the total number of aligned fixation peaks, total fixation count and total fixation duration, while the boolean metric is the presence of 0 aligned peaks. It is important to note that the boolean metric, presence of 0 aligned peaks is used to indicate whether the participant exhibited the aligned fixation peak for every aircraft pair-in-crossing. Qualitatively, a cumulative plot would be able to showcase the instances at which such aligned peaks occur, for a deeper understanding and evaluation of a participant's crossing monitoring behaviour.

Using aircraft pair-in-crossing AXM540 and TGW791 as an example, these metrics and cumulative plots for all intermediate participants are seen in both Table 5.4 and Figure 5.19 respectively. Therefore, comparisons can be performed based on the expertise group of participants and the crossing characteristics.

Table 5.4. Aligned Fixation Peaks Metric for AXM540 and TGW791 on Intermediate Participants

Aligned Fixation Peaks Metric	Number of 0 Aligned Peaks	Total Number of Aligned Peaks	Total Fixation Count	Total Fixation Duration
Participant A	0	20	72	65189
Participant B	0	4	12	17005
Participant C	0	14	69	66784
Participant D	0	4	15	12750
Participant E	0	9	39	40125

Figure 5.19. Cumulative Aligned Fixation Peaks Plot for AXM540 and TGW791 for Intermediate Participants

From Figure 5.19, three cumulative line plots of the number of aligned fixation peaks, total fixation count and total fixation duration against the elapsed frame number, for all intermediate participants were made. Every ‘step up’ increase of the line signifies that the participant exhibited an aligned fixation peak. The length of vertical increase of this line represents the proportion of the metric throughout the flight duration from the point of entry to the crossing point, for aircraft pair-in-crossing, AXM540 and TGW791. Using Figure 5.19, it is observed that different participants have different crossing monitoring behaviour, as the aligned fixation peaks were not executed at the same frame. This highlights that different individuals exhibit a different crossing monitoring behaviour when performing this task. Despite the differences in their crossing monitoring behaviour, all intermediate participants (all participants in Figure 5.19) began their crossing monitoring of AXM540 and TGW791 earlier and have more than one aligned fixation peak up till 0.5min before the crossing. Two periods of crossing monitoring behaviour, frames 0 to 6 and frames 20 to 35, were found to be exhibited by all participants. This indicates that for AXM540 and TGW791,

participants exhibited crossing monitoring behaviour at the start of the scenario and 3.6 minutes before the aircraft pair crosses. This is also consistent with findings of previous studies, as participants were found to only monitor for crossing 4 minutes prior to its occurrence [135]. Therefore, the duration when most participants monitor for the aircraft pair-in-crossing can be deduced, together with their monitoring behaviour.

5.4.4. Application of Crossing Monitoring Signature

Upon establishing aligned fixation peaks as a crossing monitoring signature, it is now applied to compare the differences in crossing monitoring behaviour among participants of different expertise levels for different crossing point characteristics.

The different crossing point instances were split into two different cases, instances when the aligned fixation peaks signature is not exhibited, as well as instances when the signature is exhibited. In both cases, analysis was performed at three different layers, to understand the difference in monitoring behaviour between the three expertise levels. The three layers represents the different crossing characteristics, which are crossing points in general, angle of crossing points (wide vs medium) and proximity of crossing points (close vs independent). Furthermore, within each layer, the differences in crossing characteristics were also analysed whenever two levels exist. For the case of crossing instances with no aligned fixation peaks, the boolean metric, number of 0 aligned peaks is used. On the other hand, for the case of crossing instance with aligned fixation peaks, the continuous metrics, total number of aligned peaks, total fixation count and total fixation duration, together with the cumulative plot of crossing instances between the participants, was used. Figure 5.20 depicts the analysis performed pictorially.

Figure 5.20. Pictorial Illustration of the Analysis of Crossing Point Instances

In this analysis, a total of 264, 220 and 484 crossing point instances were examined for novice, intermediate and expert participants respectively. For the analysis on the angle of crossing for these crossing point instances, there were 198, 165 and 363 wide angle and 66, 55 and 121 medium angle crossing point instances for novice, intermediate and expert participants respectively. On the other hand, for the analysis on the proximity of crossing for these crossing point instances, there were 126, 105 and 231 close crossing point instances and 72, 60 and 132 independent crossing point instances were used for novice, intermediate and expert participants respectively. For the analysis of location of crossing point, 4 aircraft pairs-in-crossing were selected for each of the 2 selected crossing point, giving rise to 24 novice, 20 intermediates and 44 expert crossing instances for each crossing point.

5.4.4.1. Crossing Point Instances with no aligned fixation peaks

For the crossing point instances with no aligned fixation peaks, the boolean metric, number of 0 aligned peaks were first counted for all aircraft pairs-in-crossing. This metric represents the lack of crossing monitoring behaviour of participants for a crossing point instance. The total number of 0 aligned peak instances for the three

different layers of analysis, across all three expertise groups was tabulated in Table 5.5, presented as a fraction of the total number of crossing point instance.

Table 5.5. Number of 0 Aligned Fixation Peaks for aircraft pairs-in-crossing across all 3 expertise groups

Metric 1: Number of 0 Aligned Fixation Peaks (Total 0 aligned peaks / total instances)		Novice	Intermediate	Expert
Layer 1: Generic Crossing Points	All crossing points	76/264 (0.29)	44/220 (0.2)	73/484 (0.15)
Layer 2: Angle of Crossing	Wide Angle	67/198 (0.34)	38/165 (0.23)	62/363 (0.17)
	Medium Angle	9/66 (0.14)	6/55 (0.11)	11/121 (0.09)
Layer 3: Proximity of Crossing	Close	40/126 (0.32)	21/105 (0.2)	34/231 (0.15)
	Independent	36/72 (0.5)	23/60 (0.38)	39/132 (0.3)
Layer 4: Location of Crossing	Center	7/24 (0.29)	3/20 (0.15)	7/44 (0.16)
	Corner	14/24 (0.58)	6/20 (0.3)	7/44 (0.16)

5.4.4.1.1. Effect of Expertise Level

Results from Table 5.5 shows that only 15% of expert crossing instances have no aligned fixation peaks signature detected, when looking at the crossing point instance in general. Furthermore, by considering the crossing point instances in general, novice participants are most likely to not exhibit an aligned fixation peaks signature, as seen in 29% of the crossing instances. For intermediate participants, no aligned fixation peaks signature was detected in 20% of the crossing point instances. This meant that the intermediate and novice participants are 1.33 and 1.93 times more likely to miss the monitoring of aircraft pairs-in-crossing, as opposed to expert. This is reasonable as the task of identifying aircraft pairs-in-crossing, which is to fixate

more often and longer for the aircraft pairs within a short duration, should be the most obvious to experts, followed by intermediates, then novices, owing to their experience and training. Such is found to be consistent to the information reduction theory on learned selectivity of information processing, where experts more fixations of a longer duration on task-relevant areas [138].

At the second layer, differentiating the crossing points by wide and medium angle, a similar observation can also be made, that the expert participants are least likely to miss an aircraft pair-in-crossing, followed by intermediate and novice. For wide angle crossings, 17%, 23% and 34% of these crossing instances were missed by experts, intermediates and novices respectively. For medium angle crossings, it is also found that 9%, 11% and 14% of these crossing instances were missed by experts, intermediates and novices respectively. Such meant that at wide angle crossings, intermediate and novice participants are 1.35 and 2 times more likely to miss the monitoring of aircraft pairs-in-crossing, as opposed to expert, while intermediates and novices are 1.22 and 1.55 times more likely to miss the monitoring of aircraft pairs-in-crossing for medium angle crossings. These results are consistent with that from the analysis of crossing points in general, where novices are unlikely to identify and recognise the aircraft pairs-in-crossing by fixating on them more often for a longer duration within a short time span. This points out that experts can execute the task of monitoring for aircraft pairs-in-crossing more easily, for both wide and medium angle crossing points, which is consistent with other studies, stating that expertise level affects the monitoring tasks [59, 63].

At the third layer, the crossing points are differentiated by their proximity, which are close and independent crossing points. It is found that for close crossing instances, 15%, 20% and 32% of them were missed by experts, intermediates and novices respectively, while 30%, 38% and 50% of the independent crossing instances were missed by experts, intermediates and novices respectively. Such indicates that intermediate and novice participants are 1.33 and 2.13 times more likely to miss the monitoring of aircraft flying at close crossings, compared to experts, while intermediates and novices are 1.27 and 1.67 times more likely to miss the monitoring of aircraft pairs-in-crossing for independent crossings. Similarly, these findings by

varying the proximity of crossings are agreeable to the findings of both crossing points in general and different angle of crossings, whereby experts can better perform the task of monitoring for aircraft pairs-in-crossing and novices are most likely to miss that. Referring to the theory of information reduction, experts being better trained and more experience, is thus able to identify a task-relevant area (aircraft pairs-in-crossing) and can better handle the task of monitoring them for various proximity of crossing points [138].

At the fourth layer, location of crossing, it is found that for crossing located at the center of the screen, 16%, 15% and 29% of them were missed by experts, intermediates and novices respectively, while 16%, 30% and 58% of the crossings located at the corner of the screen were missed by experts, intermediates and novices respectively. This meant that novice participants are 1.87 times more likely to miss the monitoring of aircraft flying at crossings located at the center, compared to both intermediates and experts, while intermediates and novices are 1.88 and 3.63 times more likely to miss the monitoring of aircraft pairs-in-crossing for crossings located at the corner. Such observations are likely due to the experience of experts, being able to recognise a task-relevant area on the radar screen to also monitor aircraft pairs-in-crossing at the corners [138].

5.4.4.1.2. Effect of Crossing Characteristics

Subsequently, to analyse the differences in crossing characteristics within the second and third layer, percentage figure of number of 0 aligned peaks from Table 5.5 were used and divided to obtain a ratio value. This is conducted for the three expertise, before plotting it, as seen in Figure 5.21.

Figure 5.21. Comparison of Crossing Characteristics for Number of 0 Aligned Peaks

In Figure 5.21, it is observed that participants across all expertise levels monitored differently for wide and medium crossing point instances. Expert, intermediate and novice participants are 1.89, 2.09 and 2.43 times more unlikely to exhibit the aligned fixation peaks signature on wide angle crossings as compared to medium angle ones. Such suggests that it is easier for participants across all expertise groups to exhibit aligned fixation peaks on medium angle crossing points. One possible explanation is that aircraft in medium angle crossing are spatially closer to each other geometrically as compared to wide angle crossing, thereby making it easier for consecutive monitoring between the aircraft pair-in-crossing (aligned fixation peaks) to be executed. Additionally, it is also noted that the ratio of number of 0 aligned peaks of wide angle over medium angle crossing points is the least for experts, followed by intermediates and novices. As experts are found to be able to extract information from widely distanced stimulus in many different applications [139, 140], the aligned peaks exhibited by experts for the more difficult wide angle crossing points in ATC is also found to be consistent with them. This could also likely mean that experts are better trained and more familiar in monitoring aircraft pairs-in-crossings.

By comparing close and independent crossing points in Figure 5.21, participants of all three expertise levels were also found to monitor differently for close and independent crossing point instances. Expert, intermediate and novice participants are 2, 1.9 and 1.56 times more unlikely to exhibit the aligned fixation peaks signature on independent crossings as compared to close ones. This meant that it is easier for participants of all expertise groups to exhibit aligned fixation peaks in the crossing monitoring of aircraft flying across close crossings. One possible explanation is that in areas with close crossing tend to be more crowded, as there will be a group of aircraft near to each other spatially on the radar screen. Such makes it easier to exhibit aligned fixation peaks, to ascertain if the aircraft pair will fly into crossing. This can be supported from Gestalt Law of Proximity, where “objects that are near to each other tend to be grouped together” by human beings for their perceptual organisation [141, 142]. Furthermore, the ratio of number of 0 aligned peaks of independent over close crossing points is the most for experts, followed by intermediates and novices. Such could likely mean that amongst the expert participants they are not as familiar to identifying independent crossings as compared to close crossings.

Comparing crossing points located at the corner and center of the radar screen as seen in Figure 5.21, expert participants are found to be to equally, while intermediate and novice participants are 2 times as unlikely to exhibit aligned fixation peaks signature on crossings located on the corner as compared to the center ones. This indicates that the intermediate and novice participants are likely not as familiar with the crossings located at the corner of the screen, while experts are also able to extract information from widely stimulus in many different applications [139, 140]. Such also meant that experts are better trained and more familiar in monitoring aircraft pairs-in-crossings at both the center and corners of the screen.

5.4.4.2. Crossing Point Instances with Aligned Fixation Peaks

Using the remaining 188 novice, 176 intermediate and 411 expert instances of aligned fixation peaks for the different aircraft pairs-in-crossing, the three continuous metrics, total number of aligned peaks, total fixation count and total fixation duration were computed. Differences in the monitoring of aircraft pairs-in-crossing due to various expertise levels and crossing characteristics, like the angle and proximity of crossing, were then analysed in this section.

5.4.4.2.1. Effect of Expertise Level

To compare the differences in monitoring of aircraft pairs-in-crossing due to various expertise levels on the different crossing characteristics, the descriptive statistics (sample size = N, mean = M, standard deviation = SD) of the crossing point instances were computed in Appendix C with only the mean values were listed in Table 5.6.

Table 5.6. Descriptive Statistics for Aircraft pairs-in-crossing with Aligned Fixation Peaks

		Aligned Fixation Peaks Metric	Novice	Intermediate	Expert
Layer 1	All crossing points	Total Number of Aligned Peaks	5.62	5.37	5.48
		Total Fixation Count	26.05	22.02	24.13
		Total Fixation Duration (ms)	23589.78	25109.11	22640.87
Layer 2	Wide Angle	Total Number of Aligned Peaks	5.25	4.43	4.88
		Total Fixation Count	24.22	18.48	20.96
		Total Fixation Duration (ms)	21273.42	19866.76	19706.19
	Medium Angle	Total Number of Aligned Peaks	6.46	7.80	7.12
		Total Fixation Count	30.25	31.18	32.80
		Total Fixation Duration (ms)	28913.33	38696.45	30671.20
Layer 3	Close	Total Number of Aligned Peaks	5.64	4.60	5.08
		Total Fixation Count	27.05	19.06	22.47
		Total Fixation Duration (ms)	23406.83	20968.36	21433.34
	Independent	Total Number of Aligned Peaks	5.60	6.08	5.84
		Total Fixation Count	25.21	24.72	25.65
		Total Fixation Duration (ms)	23744.03	28889.80	23752.47
Layer 4	Center	Total Number of Aligned Peaks	5.06	4.29	5.39
		Total Fixation Count	22.41	17.94	22.16
		Total Fixation Duration (ms)	20511.82	20946.76	20818.50
	Corner	Total Number of Aligned Peaks	3.20	4.29	4.11
		Total Fixation Count	11.20	14.71	16.97
		Total Fixation Duration (ms)	12130.60	14579.21	15949.78

From Table 5.6, it is observed that the sample sizes for each group are different. Hence, to examine if expertise level has a significant effect on the different metrics at different crossing characteristics, a Levene's F test, a statistical test to determine if different samples have equal variances, was then performed to determine if the homogeneity of variance assumption was met [143]. The homogeneity of variance meant that the level of variance of a variable is constant across the sample. Such is required to choose the type of statistical test to perform in order to determine whether there are any statistically significant differences between three or more means of an independent variable. In ANOVA (an established statistical test), when homogeneity of variance is violated there is a greater probability of falsely indicating that there are at least two group means that are statistically significantly different from each other [144]. Thus, results of the Levene's F test is computed and described in Appendix D. The homogeneity of variance is not met when the corresponding p-value is lesser than 0.05, at the 95% confidence level. Table 5.7 shows only the results the different metrics where such conditions are not met.

Table 5.7. Levene's F test result for homogeneity of variance on expertise level (only non-homogeneity)

Comparison of all Expertise Level		Aligned Fixation Peaks Metric	Levene's F test output
Layer 1	All Crossing Points	Total Fixation Count	$F_{2,772} = 8.671, p = 1 * 10^{-4} \approx 0 *$
Layer 2	Wide Angle	Total Number of Aligned Peaks	$F_{2,556} = 3.643, p = 0.027 *$
		Total Fixation Count	$F_{2,556} = 10.617, p = 1 * 10^{-5} \approx 0 *$
Layer 3	Close	Total Fixation Count	$F_{2,364} = 7.907, p = 1 * 10^{-4} \approx 0 *$
	Independent	Total Fixation Duration	$F_{2,405} = 4.156, p = 0.016 *$
Layer 4	Center	Total Fixation Count	$F_{2,69} = 5.897, p = 0.004 *$
		Total Fixation Duration	$F_{2,69} = 5.590, p = 0.006 *$

* indicates significance at 95% level

It is revealed that the metrics on total fixation count for all crossing points, wide angle and close crossings, together with total fixation duration on independent crossing did not meet the homogeneity of variance assumption. Hence, a Welch's F test was used for these metrics instead of a one-way ANOVA test, to compare if the expertise levels are statistically significantly different on the different aligned fixation peaks metric, for crossing points in general, wide and medium angle crossing points, as well as close and independent crossing points (characteristics of crossing points at all three layers). The results of this full one-way ANOVA and Welch F test is computed and seen in Appendix E. Therefore, if the effect of expertise level is significant, at 95% confidence level, the corresponding p-value of the one-way ANOVA or Welch F test should be less than 0.05. Hence, only the significant results were shown in Table 5.8.

Table 5.8. One way ANOVA or Welch F test results to compare the effect of expertise level on different aligned fixation peaks metric (Significant effects only)

		Aligned Fixation Peaks Metric	One way ANOVA / Welch F Test Result
Layer 2: Angle of Crossing	Wide Angle	Total Fixation Count	$F_{2,270.66} = 3.583, p = 0.030$ * (Welch)
Layer 3: Proximity of Crossing	Close	Total Fixation Count	$F_{2,179.72} = 3.936, p = 0.021$ * (Welch)

* indicates significance at 95% level

Results from Table 5.8 shows that there was a significant difference of expertise level on total fixation count at for wide angle crossings [$F(2, 556) = 3.583, p = 0.028$] and close crossings [$F(2, 364) = 3.875, p = 0.022$]. Respective post-hoc analysis was performed to determine where the differences occurred between the expertise levels, when there are three or more groups. Hence, the Tukey's honestly significant difference (HSD) post hoc test was used if homogeneity of variance was met, while the Games Howell post hoc test was when the homogeneity of variance was not met [145, 146]. Therefore, if two of the expertise groups are different, the adjusted p-value is lesser than 0.05 at 95% confidence level. Results of these post-hoc analysis is seen in Table 5.9.

Table 5.9. Post hoc analysis on statistically significant metrics

Crossing Characteristic	Aligned Fixation Peak Metric	Difference of Levels	Difference of means	Adjusted p-value
Wide Angle	Total Fixation Count (Games-Howell)	Expert – Intermediate	2.476	0.249
		Expert – Novice	-3.265	0.261
		Intermediate – Novice	-5.741	0.026 *
Close	Total Fixation Count (Games-Howell)	Expert – Intermediate	3.407	0.228
		Expert – Novice	-4.580	0.227
		Intermediate – Novice	-7.987	0.018 *

* indicates significance at 95% level

Results in Table 5.9 indicate that intermediate participants have a significantly lower total fixation count as compared to novice participants for both wide angle and close crossings. Additionally, no significant differences were found for other parameters using the results from Table 5.8 and Appendix E. Such indicates that expertise levels do not have an effect on the monitoring of aircraft pairs-in-crossing once the participant has recognised it, as seen in most of the aligned fixation peaks metrics on different crossing characteristics.

This could likely mean that participants of all expertise levels can maintain their awareness on the aircraft pairs-in-crossing after successfully identifying and recognising them in various crossing characteristics, regardless of how these aircraft pairs-in-crossing were guided. For the metrics with significant differences, it shows that intermediate participants tend to fixate lesser on aircraft pairs-in-crossing for wide angle and close crossings. Hence, with lesser fixation count and an approximately similar fixation duration for intermediate participants in wide and close crossing points, it suggests an attempt to apply the domain knowledge base, which is not fully automatized for them, based on the theory of long-term working memory for visual tasks [136, 147]. As a result, this highlights the difficulty in handling wide angle and close crossing points for intermediates, which is also investigated further in the sections to follow.

5.4.4.2.2. Effect of Crossing Characteristics

To compare the differences in monitoring of aircraft pairs-in-crossing due to crossing characteristics (wide vs medium angle, close vs independent), for all expertise levels, the same descriptive statistics (sample size = N , mean = M , standard deviation = SD) of the crossing point instances in Appendix C and the mean values in Table 5.6 was used.

Similarly, as the sample sizes for each group varies, to examine if crossing characteristic has a significant effect on the different metrics for all expertise levels, a Levene's F test was performed to determine if the homogeneity of variance assumption was met. Results of this Levene's F test is seen in Appendix F, while the conditions where the homogeneity of variance assumption was not met is listed in Table 5.10.

From Table 5.10, metrics with p -value lesser than 0.05 did not meeting the homogeneity of variance assumption, and a Welch's F test was used for these metrics instead of a one-way ANOVA test, to compare if the crossing characteristics are statistically significantly different on the different aligned fixation peaks metric, for all expertise levels. The results of this full one-way ANOVA and Welch F test is seen in Appendix G. Therefore, if the effect of crossing characteristic is significant, at 95% confidence level, the corresponding p -value of the one-way ANOVA or Welch F test should be less than 0.05 and the results of these significant effects are listed in Table 5.11.

Results from Table 5.11 and Appendix G shows that there was no significant difference on both angle and proximity of crossing on all aligned fixation peaks metric for novice participants. A significant difference on angle of crossing on all aligned fixation peaks metric is found for intermediate and expert participants. Furthermore, a significant difference on the proximity of crossing of all aligned fixation peaks metric for intermediate participants was also noted. Comparing the location of crossing points, no significant differences was found on all aligned fixation peaks metric for participants of all expertise levels. As there are only two groups in angle, proximity and location of crossings, no further post-hoc analysis is required.

Table 5.10. Levene's F test result for homogeneity of variance on Crossing Characteristics (only non-homogeneity)

Comparison of Crossing Characteristics	Expertise Level	Aligned Fixation Peaks Metric	Levene's F test output
Layer 2 (Wide vs Medium)	Novice	Total Fixation Count	$F_{1,186} = 4.263, p = 0.040 *$
		Total Fixation Duration	$F_{1,186} = 7.095, p = 0.008 *$
	Intermediate	Total Number of Aligned Peaks	$F_{1,174} = 23.8, p = 1 * 10^{-6} \approx 0 *$
		Total Fixation Count	$F_{1,174} = 15.128, p = 1 * 10^{-4} \approx 0 *$
		Total Fixation Duration	$F_{1,174} = 22.317, p = 1 * 10^{-6} \approx 0 *$
	Expert	Total Number of Aligned Peaks	$F_{1,409} = 21.710, p = 1 * 10^{-6} \approx 0 *$
		Total Fixation Count	$F_{1,409} = 18.530, p = 1 * 10^{-5} \approx 0 *$
		Total Fixation Duration	$F_{1,409} = 11.838, p = 1 * 10^{-4} \approx 0 *$
Layer 3 (Close vs Independent)	Intermediate	Total Fixation Count	$F_{1,174} = 5.445, p = 0.021 *$
		Total Fixation Duration	$F_{1,174} = 8.836, p = 0.003 *$
Layer 4 (Center vs Corner)	Novice	Total Number of Aligned Peaks	$F_{1,25} = 14.878, p = 0.001 *$
		Total Fixation Count	$F_{1,25} = 14.878, p = 1 * 10^{-5} \approx 0 *$
		Total Fixation Duration	$F_{1,25} = 14.878, p = 0.011 *$
		Total Fixation Duration	$F_{1,29} = 12.074, p = 0.002 *$

* indicates significance at 95% level

Table 5.11. One way ANOVA or Welch F test results to compare the effect of crossing characteristics on the different aligned fixation peaks metric (Significant effects only)

Comparison of Crossing Characteristics	Expertise Level	Aligned Fixation Peaks Metric	One way ANOVA / Welch F Test Result
Layer 2 (Wide vs Medium)	Novice	Total Fixation Duration	$F_{1,83.98} = 4.186, p = 0.044 *$
	Intermediate	Total Number of Aligned Peaks	$F_{1,60.307} = 19.652, p = 1 * 10^{-5} \approx 0 * (\text{Welch})$
		Total Fixation Count	$F_{1,64.498} = 15.775, p = 1 * 10^{-5} \approx 0 * (\text{Welch})$
		Total Fixation Duration	$F_{1,60.164} = 21.662, p = 1 * 10^{-5} \approx 0 * (\text{Welch})$
	Expert	Total Number of Aligned Peaks	$F_{1,152.783} = 20.330, p = 1 * 10^{-5} \approx 0 * (\text{Welch})$
		Total Fixation Count	$F_{1,158.265} = 25.908, p = 1 * 10^{-6} \approx 0 * (\text{Welch})$
		Total Fixation Duration	$F_{1,168.742} = 22.747, p = 1 * 10^{-6} \approx 0 * (\text{Welch})$
Layer 3 (Close vs Independent)	Intermediate	Total Number of Aligned Peaks	$F_{1,156.410} = 6.895, p = 0.01 * (\text{Welch})$
		Total Fixation Count	$F_{1,170.495} = 5.188, p = 0.024 * (\text{Welch})$
		Total Fixation Duration	$F_{1,158.333} = 6.839, p = 0.01 * (\text{Welch})$
Layer 4 (Center vs Corner)	Novice	Total Number of Aligned Peaks	$F_{1,24.149} = 3.556, p = 0.071 (\text{Welch})$
		Total Fixation Count	$F_{1,23.277} = 5.647, p = 0.026 * (\text{Welch})$

* indicates significance at 95% level

By comparing the means of the aligned fixation peaks metrics with significant differences, it is found that intermediate participants exhibited 0.57, 0.59 and 0.51 times lesser aligned fixation peaks, fixation count and fixation duration respectively, on wide angle crossings as compared to medium angle crossings. A similar observation is also seen in expert participants, where experts exhibited 0.69, 0.64 and 0.64 times aligned fixation peaks, fixation count and fixation duration respectively. Additionally, intermediate participants were also found to exhibit 0.76, 0.77 and 0.73

times lesser aligned fixation peaks, fixation count and fixation duration respectively on close crossings as compared to independent crossings.

Therefore, being more familiar and well-trained in guiding aircraft pairs-in-crossing, intermediate and expert participants exhibited lesser aligned fixation peaks, fixation count and fixation duration on wide angle crossings as compared to medium angle crossings, suggesting differences in monitoring behaviour. This is consistent with the findings in other studies, where licensed ATCOs are found to monitor differently as a result of the geometry of the crossing points [148, 149]. Hence, these results suggest that novice participants possibly do not know how to guide the aircraft pairs-in-crossing, as different crossing characteristics result in a similar monitoring behaviour. Furthermore, with lesser aligned fixation peaks, fixation count and fixation duration exhibited by only intermediate participants when comparing between close and independent crossings, it shows that they are also less familiar and lesser trained at handling close crossings as compared to experts. These findings are also consistent with that of the information reduction theory on visual tasks [138]. As for location of crossing point, it can be deduced that as long as the participant identified and recognised the aircraft pair-in-crossing, they are able to monitor them in an approximately similar fashion. As a result, more training on close crossings can be focused on intermediate participants, while training on guiding aircraft pairs-in-crossing on various angle and proximity can be given for novice participants. Such can aid them in achieving the same expertise level as the expert participants.

5.5. Activity Management 2 – Aircraft Frequency Switch

5.5.1. Formulation of Fixation-Click Count Signature

In this activity management, whenever there is a need for a change in aircraft frequency (be it pilot request or ATCO initiated), ATCOs would need to recognise them, which is evidenced from the clicking of the ‘UCO’ and ‘TOC’ command on the aircraft’s label. To do so, ATCOs would likely have perceived and comprehended these incoming or outgoing aircraft by fixating their track or label, before clicking on respective commands within a specified duration based on operational requirements, to perform this switch of frequency.

As a result, a signature to capture an ATCO performing this activity is proposed in this study, which can be deduced via its fixation-click count on an aircraft and the respective ‘UCO’ or ‘TOC’ command. Hence, if an ATCO would have perceived and comprehended an aircraft during this task, he / she would have at least fixated once on the aircraft (criteria 1) and clicked on the appropriate command (criteria 2), within a specific duration after the pilot’s request. Using these 2 criteria, a binary signature can then be created. Figure 5.22 shows a flowchart, depicting the process of how this signature works. The proposed fixation-click count signature is then tested on 45 selected aircraft in the scenarios, comprising of 270, 225 and 495 novice, intermediate and expert instances across the 88 experimental sessions respectively.

5.5.2. Application of Fixation-Click Count Signature

In all these sessions, the ATCO needs to take jurisdiction (perform ‘UCO’) of these aircraft as they enter the airspace and test results show that every participant across all 3 expertise groups managed to perform ‘UCO’ for them. Using the proposed fixation-click count signature, with a specified duration of 2 minutes, the number of participants across all 3 expertise groups, who have exhibited the aircraft frequency switch signature as they enter the sector by fulfilling the two criteria for all sessions, is seen in Table 5.12. In addition, Table 5.12 also showcases the proportion of participants who have fulfilled only criteria 1 and criteria 2 for all sessions respectively.

Figure 5.22. Proposed signature flowchart for aircraft frequency switch

Table 5.12. Number of Participants fulfilling the different signature criteria in UCO

	Novice	Intermediate	Expert
Number of participants who fulfilled both Criteria 1 and 2	235/270 (0.87)	212/225 (0.94)	455/495 (0.91)
Number of participants who fulfilled only Criteria 1	235/270 (0.87)	212/225 (0.94)	455/495 (0.91)
Number of participants who fulfilled only Criteria 2	270/270 (1)	225/225 (1)	495/495 (1)

From Table 5.12, it is observed that participants from all expertise groups are able to exhibit the fixation-click count signature, as an average of 91% of the participants fulfilled both Criteria 1 and 2 for ‘UCO’ command.

The proposed fixation-click count signature is also performed for aircraft leaving the airspace, where the ATCO needs to hand-over to the adjacent sector (perform ‘TOC’). Results of the number of participants across all 3 expertise groups, who have exhibited the fixation-click count signature as they leave the sector by fulfilling both the criteria, criteria 1 only and criteria 2 only, within a specified 2-minute duration, is shown in Table 5.13. Similar observations can be made for ‘TOC’ command, where participants from all expertise groups are able to exhibit the fixation-click count signature, as an average of 86% of the participants fulfilled both Criteria 1 and 2.

Table 5.13. Number of Participants fulfilling the different signature criteria in TOC

	Novice	Intermediate	Expert
Number of participants who fulfilled both Criteria 1 and 2	231/270 (0.86)	196/225 (0.87)	425/495 (0.86)
Number of participants who fulfilled only Criteria 1	231/270 (0.86)	196/225 (0.87)	425/495 (0.86)
Number of participants who fulfilled only Criteria 2	258/270 (0.96)	215/225 (0.96)	470/495 (0.95)

These observations show that the two criteria forming the fixation-click count signature are noticeable actions for all participants for both ‘UCO’ and ‘TOC’ commands. This mean that fixating on the aircraft and clicking on the respective commands on the aircraft’s label, whenever there is a need for a frequency switch, indicates a common action amongst participants. Therefore, the new fixation-click count signature could be used as a suitable measure to identify if a participant has perceived and comprehended an aircraft during this activity.

5.6. Activity Management 3 – Generic Flight Path monitoring

Two approaches, macroscopic aircraft eye metric and combined fixation-mouse over label, are explored to identify the signature of how an ATCO would perceive and comprehend for the activity of generic flight path monitoring. To do so, the ATCO would likely have fixated on the aircraft's track or label deliberately throughout the course of its flight across the airspace sector, so as to be aware of the aircraft's flight state.

5.6.1. Approach 1: Macroscopic Monitoring Eye Metric

Macroscopic eye metric like the total number of fixation count and total fixation duration, was correlated with the aircraft characteristics in a sector to identify a signature, by understanding the relationship between flight distance and change in Flight Level (FL) (climbing or descending aircraft) with total fixation count and total fixation duration on the aircraft of interest. Furthermore, there is also a need to understand if there is regular monitoring occurring.

Table 5.14 shows the flight distance and change in FL of 5 selected aircraft that will be used for this comparison. The total fixation count and mean total fixation duration, for participants from each expertise group for the whole flight path of the selected aircraft within the sector is computed.

Table 5.14. Flight Parameters and Eye Tracking Metrics of Selected Aircraft for Comparison

Callsign	Flight Distance (NM)	Change in FL
THA470	228	0
TGW516	180	0
TGW993	108	0
CPA810	108	-40

By comparing THA470, TGW516 and TGW993 to investigate the effect of flight distance on total fixation count and total fixation duration, the mean of these metrics was computed. On the other hand, to investigate the effect of changing FL, TGW993 and CPA810 were compared. The results of these computation were seen in Table 5.15.

Table 5.15. Mean Fixation Count and Fixation Duration on Flight Distance and Flight Level changes across expertise levels

		Flight Distance			Flight Level (FL)	
		Aircraft Callsign				
		THA470	TGW516	TGW993	TGW993	CPA810
Mean Fixation Count	Novice	100.8	70.3	29.3	29.3	55.8
	Intermediate	62.6	64.0	29.2	29.2	40.8
	Expert	94.5	52.4	16.5	16.5	45.7
Mean Fixation Duration (ms)	Novice	86407.0	63706.8	24849.5	24849.5	38891.2
	Intermediate	58613.0	57032.2	28864.8	28864.8	43410.2
	Expert	77136.5	40977.2	12966.2	12966.2	42465.2

From Table 5.15, it is observed that the trend, as flight distance decreases, the mean fixation count and mean fixation duration decreases is only applicable for novice and expert participants, but not intermediate participants. In addition, for aircraft with a changing FL, there is an increase in the mean fixation count and mean fixation duration. However, these metrics are unable to determine if participants were monitoring the aircraft regularly and consistently along its flight path.

This indicates that a generic measure of total fixation count and total fixation duration is too coarse in identifying the monitoring behaviour of aircraft flying along a flight path, as unintended fixations were also counted. As generic flight path monitoring is a multi-tasking activity, ATCOs are unable to monitor an aircraft more often for a longer duration due to its flight configuration, as a time spent monitoring another aircraft would result in less time to monitor for the specified aircraft. For an ATCO to be managing this multi-tasking activity, they are only required to be monitoring the aircraft intermittently, to maintain his awareness of the aircraft [18, 150].

Due to the inability of using general measurements to account for the listed factors, it is not suitable as a signature for measuring an ATCO's generic flight path monitoring behaviour.

5.6.2. Approach 2: Combined Fixation-Mouse over Label

As a general use of total fixation count and total fixation duration did not yield any favourable result which can explain an ATCO's generic flight path monitoring behaviour, an attempt was made to investigate the combination of fixation count and number of 'mouse-over' of aircraft label. Every 'mouse-over' label can be for the purpose of selecting an aircraft label (SAA), issuing clearances, like taking jurisdiction of aircraft upon entry to sector (UCO), handing over the jurisdiction of aircraft upon leaving sector (TOC), clearing an aircraft to climb or descend to a specific FL (EFL), clearing the aircraft to fly on a specified heading (HDG) by clicking on fields in an aircraft label on the radar display. Hence, a time series of an ATCO's fixation and 'mouse-over' on a particular aircraft's label were superimposed and plotted, for a better visualisation of the ATCO's eye and hand physiological signals for this aircraft across time. Figure 5.23 shows this time series plot, for one such participant (expert)'s eye and hand movement physiological signal for flight CPA810.

In Figure 5.23, each blue dot represents a fixation, with its value corresponding to the elapsed time in seconds and also its fixation duration in milliseconds (ms). Subsequently, each vertical line drawn represents a 'mouse-over' label, while its respective colour shows its corresponding command on its label. From Figure 5.23, it is observed that there are several instances where an ATCO exhibits fixation and 'mouse-over' of aircraft label very close to each other in time, while there are also instances where fixations occur with no 'mouse-over' of label nearby and vice versa. This indicates that whenever fixations and 'mouse-over' occurs very close in time, the ATCO is active in deliberately fixating on the aircraft during the course of its flight, to maintain his awareness of it or to issue appropriate commands, for its flight path monitoring. Observations of the different 'mouse-over' of label with fixations occurring shows its occurrence intermittently.

Figure 5.23. Time Series Plot of a Participant's Eye and Hand movement for CPA810

As a result, these ‘mouse-over’ labels which can be termed as Radar Commands (RC) and the time intervals of RC with fixations within it, could be used as a possible signature to describe how an ATCO perceives and comprehends an aircraft in the generic flight path monitoring task. These results showcased the potential of approach 2 in capturing and evaluating how an ATCO would perceive and comprehend an aircraft, hence efforts to identify a suitable signature should be targeted at combining both the eye and hand movement data in this manner.

5.6.3. Formulation of RCG Time Entropy Signature.

By combining both the eye and hand movement data of the ATCO, different Radar Command intervals with fixations within it can be formed. This would give rise to several Radar Command Groups (RCG) across time and a RCG time entropy signature can then be formulated. Figure 5.24 shows an overview of the entire formulation process of this signature, which is performed in three phases. A detailed explanation of the formulation of the RCG time entropy signature is discussed in the ensuing sections.

Figure 5.24. Overview of Generic Flight Path Monitoring Signature

5.6.3.1. Phase 1: Identification of RCG

In Phase 1 of this formulation of RCG time entropy signature, there is a need to first ascertain the definition of an RCG. Based on the observation from Approach 2, an RCG is a fixed time interval that consists of one or several ‘mouse-over’ of an aircraft labels, with at least one fixation within it. RC occurring in the same frame will be grouped together. The time interval of this group is then set using the timestamp of the first and last of such ‘mouse-over’ labels within this group, together with the consideration of a half frame tolerance of 4.9 seconds, as fixations on the aircraft can happen slightly before and after a ‘mouse-over’ label event. It is important to note that each ‘mouse-over’ represents the mouse moving over the label or the ATCO issuing commands to the aircraft. After setting the time interval, an RC Group (RCG) is only formed if there is at least one fixation on the aircraft that falls within this duration.

5.6.3.2. Phase 2: Construction of RCG Time Profile

Upon identifying an RCG, the different RCGs present in the generic flight path of an aircraft can then be plotted across time, together with its corresponding sum of fixation count and fixation duration, as the aircraft flies across its flight path in the sector. Figure 5.25 shows an example of an RCG time profile for one such participant

for aircraft EVA707. Different RCG types are labelled with a different colour, with each colour signifying a key task that the participant is executing. The 3 key tasks are namely, ‘crossing monitoring’, ‘UCO’ and ‘TOC’. The other RCG not belonging to these 3 key tasks are labelled as ‘Generic’. If there are 2 out of the 3 key tasks occurring at the same RCG, a separate colour is assigned to the RCG. Hence, a total of six different RCG types were derived accordingly. The vertical height of the bar directly corresponds to the fixation count and fixation duration in the vertical axis. As the RCG can span from a minimum of 1 frame duration to several frames, hence, the thickness of the bar represents the duration which the RCG spans across.

Figure 5.25. RCG Time Profile for EVA707 for one such participant

From Figure 5.25, it is observed that the participant has exhibited all 3 key tasks in their RCG time profile. By comparing the fixation count and fixation duration of each RCG, the RCG at frame 52 (crossing) has more fixation duration than fixation count. Deeper investigation reveals that at this RCG, the participant is issuing a clearance for EVA707 to climb, thereby resulting in more information processing required.

Based on the RCG time profile as seen in Figure 5.25, it is observed that a participant would exhibit RCGs across the entire sector occupancy of an aircraft. As a result, it can be said that for an ATCO to be perceiving and comprehending an aircraft

regularly for a generic flight path monitoring task, there should be a minimum number of RCGs, which are spread out regularly across the time profile.

5.6.3.3. Phase 3: Calculating RCG Time Entropy

The RCG time profile can be evaluated by assessing the number of RCGs and the consistency (regularity) of the RCG time profile, to determine if a participant has fixated on the aircraft's track or label deliberately throughout the course of its flight across the airspace sector. To do so, information entropy of the RCG time profile is calculated.

In the last twenty years, entropy methods are increasingly popular and used commonly to define periodicity or regularity in human data has become quite popular [151]. Entropy has been used to describe changes in human physiological signals like postural control [152, 153], physical activity measures [154], as well as movement tasks [155, 156].

Information entropy by Shannon is a foundational concept of information theory, and it quantifies the amount of information in a variable [157]. It is important to note that this amount of information is not just a count of the information available, it also proportional to the amount of 'surprise' (gain) of the information. Hence, Shannon's information entropy quantifies the absolute minimum amount of information (knowledge) gain. Information gain is defined as the inverse of probability of an event occurring, as the lower the probability of an event occurring, the larger the information gain, as seen in (5-1). In (5-2), Shannon's information entropy is shown, and it is equals to the sum of probability of information gain from all events. It is also observed from (5-2) that information entropy considers both the quantity and quality of information gained.

$$I_i = \frac{1}{p_i} \quad (5-1)$$

$$H(p) = \sum_{i=1}^n p_i \log I_i = - \sum_{i=1}^n p_i \log p_i \quad (5-2)$$

Information entropy has been applied on many applications involving discrete signals, like financial data analysis, computing networks and many more [158, 159]. A discrete signal source is defined as a system which produces a sequence of symbols governed by a set of probabilities [160]. For the RCG time profile, the process of determining if an RCG exists across the course of an aircraft's flight in a sector at any point of time, is a way to discretise the continuous eye and hand movement of a participant. Therefore, information entropy can be applied on the RCG time profile of a participant on an aircraft, where a higher information entropy mean a higher information gained by an ATCO of the aircraft during its generic flight monitoring activity.

Using information entropy to compute the regularity of an RCG time profile, the duration of an aircraft in the sector is first computed. Subsequently, the time difference between individual RCG across time is calculated, by taking the difference in the frame number between the end of current RCG and the start of the next RCG. It is important to note that a reference RCG is positioned intentionally at the start and end of every flight path profile for the information entropy computation, so as to denote the instant where the aircraft enters and leaves the airspace respectively. From the list of time differences, the probability of each time difference occurring is calculated using (5-3), before applying it to (5-2).

$$Probability = \frac{Time\ Difference}{Flight\ Duration} \quad (5-4)$$

Using this calculation and understanding of information entropy in quantifying the regularity of RCG time profile, a set of information entropy values for different RCG time profile is calculated to determine the RCG time entropy value, so as to ascertain a proper interpretation of them for the ATCO. Figure 5.26 provides a description of these different cases of RCG time profile and the corresponding RCG time entropy value for Aircraft X, with the same start and end reference frame.

Figure 5.26. Illustration of different RCG time profile cases with their respective Information Entropy value

By comparing cases 1 and 2, cases 3 and 6, one extra RCG results in a higher information entropy value, despite the same time interval between each individual RCG. This means that every new RCG will result in more information gain by the ATCO, which is reflective of a regular generic flight path monitoring. Comparing cases 2 and 3, a larger duration between RCG, 18 frames for case 2 and 4 frames for case 3 also results in a larger information entropy. This shows that if an ATCO tends to monitor the aircraft closely in time and not monitor again, information gained by the ATCO is lesser, which is also reflective of the need to monitor the aircraft during its flight duration more regularly. Furthermore, by comparing cases 3, 4 and 5, where all cases have 4 RCGs that are spaced 4 frames apart individually, a first RCG occurring 39 frames after an aircraft enters the sector results in a higher information

entropy value as opposed to the first RCG occurring 1 frame and 77 frames after an aircraft enters the sector. Such observation is also reflective of the regularity in the generic flight path monitoring of ATCOs, as the information gained by an ATCO only when he monitors early or late is lesser as compared to one who monitors in the middle. Lastly, case 7 shows an RCG time profile, with 6 RCGs that are randomly spaced. It has the highest information entropy value among all the cases and reflective of a regular generic flight path monitoring of ATCOs, where he monitors throughout the flight path profile regularly, with the intervals spaced randomly.

As a result, for Aircraft X, a higher RCG time entropy value signifies that an ATCO has fixated on the aircraft's track or label deliberately more regularly, by either exhibiting the RCG more often or more consistently throughout the course of its flight. Hence, a higher RCG time entropy value would mean a more regular generic flight path monitoring behaviour from an ATCO for that aircraft.

5.6.4. Application of RCG Time Entropy Signature

To illustrate the proposed RCG time entropy signature, the construction of RCG time profile and calculation of the RCG time entropy value is applied to 48 selected aircraft of different flight configurations, comprising a total of 288 novice, 240 intermediate and 528 expert instances. The RCG time entropy calculation is first applied to aircraft CPA810 for a proper illustration, before evaluating it on all aircraft from the different sessions.

5.6.4.1. Evaluation of RCG Time Profile Signature on CPA810

Using CPA810, its RCG time profile for every participant can be constructed. Figure 5.27 shows an example of the RCG time profile on CPA810 for one expert participant. Using the constructed RCG time profile for every participant, their respective RCG time entropy value can be calculated. The distribution of the RCG time entropy value of all participants across the three expertise groups for CPA810 is plotted and shown in Figure 5.28.

Figure 5.27. RCG time profile for CPA810 of 1 Expert Participant

Figure 5.28. Distribution of RCG Time Entropy Value of CPA810 for all Participants

From Figure 5.28, it is observed that the maximum RCG time entropy value from the novice participants is the lowest (2.03) among the three different expertise groups

and the expert participants have the smallest variation of the RCG time entropy values. It is found that the standard deviation of RCG time entropy value of experts (0.36) is the least and is 36% and 53% less than intermediate (0.56) and novice (0.75) participants respectively. These results indicate that the expert participants are more consistent in their generic flight path monitoring behaviour as compared to participants of other expertise group, owing to their experience and expertise. This can be viewed as experts having more RCGs and RCGs that are more regularly spaced in general, for CPA810.

5.6.4.2. Evaluation for all other aircraft

To illustrate the proposed RCG time entropy signature, the construction of RCG time profile and calculation of the RCG time entropy value is being applied to 12 selected aircraft of different flight path configurations, comprising a total of 72 novice, 60 intermediate and 121 expert instances.

Differences in the generic flight path monitoring of aircraft due to various expertise levels and flight path configuration, were then analysed in this section. These instances comprised of four different flight path configurations, which is described in Table 5.16. To compare these differences, descriptive statistics (sample size = N, mean = M, standard deviation = SD) of the RCG time entropy values were first listed in Table 5.17.

Table 5.16. Description of different Flight Path Configuration

Flight path configuration	Flight Distance (NM)	Change in FL	Number of Crossing	Flight Segment
1	228	0	1	Entry > Airway > Crossing > Airway > Exit
2	108	-40	1	Entry > Crossing > Exit
3	123	70	1	Entry > Crossing > Airway > Exit
4	110	100	1	Entry > Airway > Crossing > Exit

Table 5.17. Descriptive Statistics of the RCG Time Entropy Value for the different flight path configuration across expertise level

Flight path configuration	Novice	Intermediate	Expert
1	N = 18, M = 2.10, SD = 0.629	N = 15, M = 2.40, SD = 0.384	N = 33, M = 2.12, SD = 0.336
2	N = 18, M = 1.56, SD = 0.597	N = 15, M = 1.82, SD = 0.469	N = 33, M = 1.63, SD = 0.467
3	N = 18, M = 1.17, SD = 0.926	N = 15, M = 1.70, SD = 0.647	N = 33, M = 1.83, SD = 0.504
4	N = 18, M = 1.53, SD = 0.568	N = 15, M = 1.71, SD = 0.493	N = 33, M = 1.83, SD = 0.388

5.6.4.2.1. Effect of Expertise Level

From Table 5.17, it is observed that the sample sizes for each expertise group are different. Hence, a Levene's F test, a statistical test to determine if different samples have equal variances, was then performed to determine if the homogeneity of variance assumption was met [143], prior to examining if expertise level has a significant effect on the different metrics at different crossing characteristics. The homogeneity of variance assumption is a requirement to choose the type of statistical test to perform, in order to determine whether there are any statistically significant differences between three or more means of an independent variable. Hence, ANOVA (an established statistical test) is used when the homogeneity of variance is met [144], otherwise the Welch's F Test is used. Thus, results of the Levene's F test is seen in Table 5.18 and the homogeneity of variance is not met when the corresponding p-value is lesser than 0.05, at the 95% confidence level.

Table 5.18. Levene's F Test Result for Homogeneity of Variance on Expertise Level

Flight path configuration	Levene's F test output
1	$F_{2,63} = 3.264, p = 0.045 *$
2	$F_{2,63} = 1.282, p = 0.285$
3	$F_{2,63} = 5.250, p = 0.08 *$
4	$F_{2,63} = 1.609, p = 0.208$

* indicates significance at 95% level

From Table 5.18, it is revealed that the metrics on total fixation count for all crossing points, wide angle and close crossings, together with total fixation duration on independent crossing did not meet the homogeneity of variance assumption. Hence, the respective ANOVA and Welch F test are performed to compare if the expertise levels are statistically significantly different on the different flight path configurations, as seen in Table 5.19. Therefore, if the effect of expertise level is significant, at 95% confidence level, the corresponding p-value of the one-way ANOVA or Welch F test should be less than 0.05.

Table 5.19. One way ANOVA or Welch F Test Results to compare the effect of Expertise Level on Different Flight Path Configuration

Flight path configuration	One way ANOVA / Welch F Test Result
1	$F_{2,28.67} = 3.145, p = 0.058$ (Welch)
2	$F_{2,63} = 1.107, p = 0.337$
3	$F_{2,27.828} = 3.878, p = 0.033$ (Welch) *
4	$F_{2,63} = 2.264, p = 0.112$

* indicates significance at 95% level

Results from Table 5.19 shows that there was a significant difference of expertise level at flight path configuration 3. Respective post-hoc analysis were then performed to determine where the differences occurred between the expertise levels, when there

are three or more groups. Hence, the Tukey's honestly significant difference (HSD) post hoc test and Games Howell post hoc test was used when homogeneity of variance was met and not met respectively [145, 146]. Therefore, if two of the expertise groups are different, the adjusted p-value is lesser than 0.05 at 95% confidence level. Results of these post-hoc analysis is seen in Table 5.20.

Table 5.20. Post Hoc Analysis on Statistically Significant Metrics

Flight path configuration	Difference of Levels	Difference of means	Adjusted p-value
3 (Games-Howell)	Expert – Intermediate	0.139	0.746
	Expert – Novice	0.660	0.026 *
	Intermediate – Novice	0.521	0.157

* indicates significance at 95% level

Results in Table 5.20 indicate that novice participants have a significantly lower RCG time entropy value as compared to expert participants for flight path configuration 3. Additionally, no significant differences were found for other parameters using the results from Table 5.19. Such indicates that expertise levels do not influence the generic flight path monitoring of aircraft on flight path configuration 1, 2 and 4, whereas only novices are found to monitor less regularly as compared to expert participants on flight path configuration 3.

This could likely mean that participants of all expertise level are able to maintain their awareness on an aircraft flying through the airspace in general for all flight path configuration, except for novice participants on flight path configuration 3. Such suggests that it is more difficult for novice participants to maintain regular awareness on the aircraft, by perceiving and comprehending on its general flight on flight path configuration 3. Hence, more training on flight path configuration 3 could be catered for novice participants.

Additionally, these results also suggest that intermediate participants could maintain their awareness on aircraft on approximately the same level as experts, based on the different flight path configuration. This suggests that the generic flight path monitoring activity on the different flight configurations for intermediate participants could be close to a fully automatized task for them, just like the experts, based on the theory of long-term working memory for visual tasks [136, 147].

5.6.4.2.2. Effect on Flight Path Configuration

To compare the differences in generic flight path monitoring behaviour due to flight path configuration for all expertise levels, the same descriptive statistics (sample size = N, mean = M, standard deviation = SD) of the crossing point instances in Table 5.17 was used.

In this comparison, the sample sizes for each flight path configuration is the same. Such meant that the homogeneity of variance assumption was met and there is no need to perform a Levene's F test. ANOVA can then be performed to determine if the flight path configurations are statistically significantly different on the different expertise level, as seen in Table 5.21.

Table 5.21. One way ANOVA Test Result to compare the effect of Flight Path Configuration on Different Expertise Level

Expertise Level	One way ANOVA Test Result
Novice	$F_{3,68} = 5.392, p = 0.002 *$
Intermediate	$F_{3,56} = 6.463, p = 0.001 *$
Expert	$F_{3,128} = 7.118, p = 1 * 10^{-4} \approx 0 *$

* indicates significance at 95% level

Results from Table 5.21 shows that there is a significant difference of flight path configuration for all expertise levels. A Tukey's HSD post hoc test was then performed to determine where the differences occurred between the flight path configurations, when there are three or more groups. Similarly, if two flight path configurations are different, the adjusted p-value is lesser than 0.05 at 95% confidence level. Results of this post hoc analysis is seen in Table 5.22.

Table 5.22. Post Hoc Analysis on Statistically Significant Metrics

Flight path configuration	Difference of Levels	Difference of means	Adjusted p-value
Novice (Tukey's HSD)	1 – 2	0.533	0.108
	1 – 3	0.923	0.001 *
	1 – 4	0.563	0.081
	2 – 3	0.390	0.340
	2 – 4	0.297	0.999
	3 – 4	-0.360	0.411
Intermediate (Tukey's HSD)	1 – 2	0.582	0.014 *
	1 – 3	0.705	0.002 *
	1 – 4	0.685	0.003 *
	2 – 3	0.123	0.910
	2 – 4	0.103	0.944
	3 – 4	-0.020	1.000
Expert (Tukey's HSD)	1 – 2	0.484	$1 * 10^{-5} \approx 0 *$
	1 – 3	0.282	0.042 *
	1 – 4	0.291	0.033 *
	2 – 3	-0.202	0.229
	2 – 4	-0.192	0.268
	3 – 4	0.009	1.000

* indicates significance at 95% level

Results in Table 5.22 indicate that flight path configuration 1 have significantly higher RCG time entropy value as compared to other flight path configurations for intermediate and expert participants. Additionally, no significant differences were found between flight path configuration 2, 3 and 4 for both intermediate and expert participants. For novice participants, only flight path configuration 1 is significantly higher than flight path configuration 3. Such indicates that flight path configuration influences the generic flight path monitoring of aircraft more for intermediate and expert participants.

These results suggest that a longer flight distance likely results in a more regular generic flight path monitoring of aircraft, as seen in the higher RCG time entropy value for flight path configuration 1. Additionally, this behaviour is more distinct for both intermediate and expert participants, indicating that they are more aware of aircraft on a longer flight duration as compared to novice participants. This could be explained by the information reduction theory of visual tasks, where a more trained participants is able to prioritise monitoring on task-relevant areas as opposed to task-redundant area [138]. Hence, for the novice participants, the lack of training or familiarity with such flights suggests that they are less able to prioritise their monitoring behaviour, resulting in them being less able to maintain regular awareness on aircraft flying a longer distance, with no change of FL in the airspace.

It is also noted that participants of all expertise could maintain their awareness on aircraft flying a shorter distance with changing FL, as seen in flight path configuration 2, 3 and 4. This suggests that a shorter distance and changing FL is easier for all participants, as participants are actively seeking to issue a command in a short time. This makes it easier for participants to maintain regular awareness on these aircraft, depending lesser on their training and familiarity.

As a result, more training aids could be directed on an aircraft's flight path configuration with lesser need for commands to be issued, for novice participants. These differences could also be used to differentiate the novice participants from intermediate and expert participants.

5.7. Summary of findings

Three different signatures involving both eye and hand movement physiological signals, each describing and quantifying how an ATCO would perceive and comprehend the different elements on the radar display is established for the different tactical monitoring activity. Each signature identified the different aspects an ATCO would have perceived and comprehended the aircraft on the radar screen, for each of the tactical monitoring activities. As a result, new eye metrics derived from these signatures can be used to evaluate the perception and comprehension of the ATCOs in their tactical monitoring activities.

For the activity of managing aircraft crossing with potential conflict, the signature of aligned fixation peaks is presented. This signature seeks to model the monitoring behaviour of ATCOs for the activity of managing aircraft crossing with potential conflict, using eye tracking technique. Information is acquired by identifying an ATCO's deliberate monitoring of the selected aircraft pair-in-crossing for comparing it within a short span of time, to determine if there is a potential conflict. Subsequent, this monitoring behaviour is represented using the aligned fixation peaks signature. As a result, this signature could indicate the instance and represent how an ATCO have perceived and comprehended the aircraft pair-in-crossing accordingly.

This acquisition and representation of how an ATCO perceives and comprehends an aircraft pairs-in-crossing is achieved by first identifying the respective fixation count and duration peaks before aligning them. Metrics such as the number of 0 aligned peaks (lack of signature), total number of aligned fixation peaks, total fixation count and total fixation duration of these aligned fixation peaks, were derived to evaluate the aligned fixation peaks signature. Test validation conducted on the aligned fixation peaks signature also shows a strong relationship between the number of aligned fixation peaks and aircraft pair flying across the same crossing point, as well as the presence of this signature among participants of all expertise level. Therefore, this signature represents instances when ATCOs are either attempting to determine the right aircraft pair-in-crossing or continuing to manage the activity of aircraft crossing with potential conflict.

Results from the analysis of crossing instances with no aligned fixation peaks showed that regardless of the different crossing point characteristics, expert participants missed the monitoring of aircraft pairs-in-crossing the least, followed by intermediates, then novice participants. Such highlights with more experience and higher expertise, participants tend to perform better in the identifying and recognising of aircraft pairs-in-crossing, as they are able to identify the task-relevant and task-redundant areas [138]. Comparing the different crossing point characteristics, it is found that medium angle, close crossings and those located at the center of the screen are easier to monitor, as participants of all three expertise levels missed the monitoring of these aircraft pairs-in-crossing the least. For the angle of crossing, this can likely be attributed to the geometry of the crossing point, as medium angle crossings are spatially closer to each other as compared to wide angle crossings, making it easier for aligned fixation peaks to be exhibited [63]. For the proximity of crossing, one likely reason is that objects that are nearer together tend to be perceived as group by human beings, thereby making it easier for aligned fixation peaks to be exhibited on close crossings [141, 142]. For the location of crossing, it is also likely attributed to the experts, identifying the corners of the screen as a task-relevant area as well [138]. Further observations can also be made when comparing within individual expertise groups. For the experts, they are found to miss lesser aircraft pairs-in-crossing for wide angle crossings and most aircraft pairs-in-crossing for independent crossings. Such can likely be mean that the expert participants are still not as familiar in identifying and recognising independent crossings.

For crossing instances when participants exhibited aligned fixation peaks, there is a lesser effect on the expertise level, as no significant difference is found for most of the aligned fixation peaks metrics, when comparing at individual crossing characteristics. Moreover, it is found that intermediate and expert participants tend to have more aligned peaks, fixation count and fixation duration on medium angle crossings, but not for novices. As a result, such suggests that novice participants do not have the right expertise and experience in guiding aircraft for different angle and proximity of crossings. This is found to be consistent with other studies, where experienced participants and licensed ATCOs are found to monitor differently as a result of the geometry of the crossing points [148, 149]. Additionally, intermediate

participants are found to exhibit more aligned peaks, fixation count and fixation duration on independent crossing points. These findings are also consistent with that of the information reduction theory on visual tasks [138]. As for location of crossing point, it can be deduced that as long as the participant identified and recognised the aircraft pair-in-crossing, they are able to monitor them in an approximately similar fashion.

Therefore, these results show that aligned fixation peaks signature can be used as a measure, to understand the variation in a participant's monitoring behaviour, due to angle and proximity of crossings, as well as expertise level. In addition, it can be used as a measure to differentiate the expertise level of the participants and understand the differences in their crossing monitoring behaviour when managing aircraft crossing with potential conflict. In the training of prospective ATCOs, the aligned fixation peaks signature can also be used, so that the trainees would better able to identify the different aircraft pairs-in-crossing and monitor them based on their crossing characteristics.

Efforts can thus be made to aid ATCOs in the monitoring of wide angle crossing and with more time dedicated to training prospective ATCOs in the handling of wide angle crossing. Similar efforts in training can also be dedicated in the monitoring of both close and independent crossing points. A performance scorecard can also be created, using the metrics of the aligned fixation peaks, to determine and benchmark an ATCO's expertise level. Lastly, this signature could also pave the way for the representation of an operator's visual monitoring behaviour in other surveillance domains, like vehicular operation.

For the activity of managing aircraft frequency switch, a fixation-click count signature involving the ATCO's fixating on the track or label of incoming or outgoing aircraft, before clicking on respective commands within a specified duration based on operational requirements, is proposed. This signature captures the perception and comprehension of ATCOs when performing the switch of aircraft frequency.

Results of both incoming and outgoing aircraft shows that 91% and 86% of the participants are able to exhibit fixation on the aircraft's track or label before clicking

on the appropriate commands respectively. Such indicates a common action amongst participants. Therefore, the fixation-click count signature could be used as a suitable measure to identify if a participant has perceived and comprehended an aircraft during this activity.

For the activity of generic flight path monitoring, the RCG time entropy signature is presented. This signature seeks to model the monitoring behaviour of ATCOs for the activity of generic flight path monitoring, by using RCG, which comprises of fixations and mouseover label actions occurring an aircraft closely in time. This is a suitable measure as it is found that whenever fixations and ‘mouse-over’ labels occur very closely in time, an ATCO is active in deliberately fixating on the aircraft during its flight, to maintain his awareness of it or to issue appropriate commands, for its generic flight path monitoring. The regularity of an ATCO’s generic flight path monitoring behaviour is determined by first constructing an RCG time profile before evaluating it using the information entropy value of it. As a result, this signature could indicate the how frequent and regular an ATCO have perceived and comprehended the aircraft on its generic flight path, where a larger RCG time entropy value represents a higher level of regularity and consistency of the RCG time profile.

Experiments conducted on 12 selected aircraft of different flight path configurations using a real time, high-fidelity simulation showed a difference in the generic flight path monitoring behaviour due to expertise and flight path configuration. Test results showed that novice participants lack the training and are less familiar in maintaining regular awareness on an aircraft’s generic flight path. Such is due to novices monitoring less regularly both on flight path configuration 3 and for aircraft flying on a longer flight distance, as compared to other expertise levels. For intermediate and expert participants, test results showed that intermediate participants are trained to the level of experts, as they could exhibit a similar level of regular awareness on an aircraft’s generic flight path monitoring. Such is seen in both comparisons of expertise level and flight path configuration, where no significant difference in RCG time entropy value was found between intermediate and experts at various flight path configurations, as well as both participant groups exhibiting more regular awareness on aircraft with a longer flight distance. Such findings are consistent with the

information reduction theory of visual tasks, where a more trained participants is able to prioritise monitoring on task-relevant areas as opposed to task-redundant area [138].

Therefore, these results showed that the RCG time entropy signature is a suitable measure for understanding differences in an ATCO's generic flight path monitoring of aircraft, due to flight path configuration and expertise levels. Hence, it can also be used to differentiate the expertise level of ATCOs and also in the training of prospective ATCOs, where trainees can better monitor the generic flight path of aircraft, based on their flight path configurations.

Efforts can thus be catered to the monitoring of aircraft flying on a longer flight distance, while alerts can also be set whenever the RCG time entropy of the ATCO falls below a fixed number for different flight path configurations. Lastly, this signature could also pave the way for the representation of an operator's visual monitoring behaviour in other surveillance domains, like vehicular operation.

The three signatures presented highlight how the perception and comprehension of ATCO can be captured and evaluated for the three key tactical monitoring activity that needs to be managed. The aligned fixation peak signature, fixation-click count signature and RCG time entropy signature can determine the crossing monitoring, aircraft frequency switch and generic flight path monitoring behaviour of ATCOs respectively. Differences in the monitoring behaviour were observed between expertise level and also between the characteristics of these different activities. For crossing monitoring activity, participants with more experience are more likely to exhibit aligned fixation peaks, whereas for generic flight path monitoring activity, participants with more experience tend to be more consistent in exhibiting RCGs on the aircraft. These signatures can thus be used to distinguish the monitoring behaviour of participants across different expertise level and also for assisting ATCOs in their tactical monitoring tasks under various circumstances. For the aircraft frequency switch activity, the action of fixation-click is noticeable for participants for both 'UCO' and 'TOC' commands. As a result, alerts can be triggered operationally when ATCOs failed to perform at a specified level and the training of prospective ATCOs

can thus evaluated more objectively by instructors. This would pave the way for new operational standards and training methods to be developed in future.

6. Chapter 6 Overall Model Evaluation

In this chapter, the use of the proposed eye-hand movement model of an ATCO's tactical monitoring activity, for traffic complexity evaluation and monitoring enhancement is presented. Two tactical monitoring activities, aircraft crossing with potential conflict and generic flight path monitoring, are used for the integration of both traffic complexity and monitoring performance from both dynamic radar and human data streams in real time, synchronously. In doing so, the monitoring strategy of an ATCO can be inferred and showcased accordingly. It must be noted that these two activities are selected, as they make up majority of the ATCO's tactical monitoring activity [12, 18].

6.1. Overall Evaluation of Aircraft crossing with potential conflict

Using AXM540 and TGW971, an aircraft pair-in-crossing with potential conflict, its evaluated traffic complexity and aligned fixation peak signature is integrated, to deduce the likely monitoring strategy of the ATCO.

To do so, the tactical traffic complexity and eye signatures are computed for the traffic complexity evaluation and monitoring enhancement of ATCO. For AXM540 and TGW971, they are already present in the airspace (on the radar screen) at the start of the simulation exercise (frame 0) and crosses the waypoint MABAL at frame 42. TGW971 is entering at FL 360 and cleared to descend to FL 300, while AXM540 is cruising at FL340.

From the data extracted of one expert participant, the lateral and vertical CAL value across time between AXM540 and TGW971 are plotted based on the aircraft position as the simulation elapses, as seen in Figure 6.1. In addition, the aligned fixation peak profile is also computed and seen in Figure 6.2. These highlight the ability of the proposed system in identifying both the CAL value and eye signature for the selected aircraft pair-in-crossing, for the corresponding crossing duration, from frame 0 to frame 42.

Figure 6.1. Lateral and Vertical CAL plot of AXM540 and TGW971

Figure 6.2. Aligned Fixation Peak Profile of Expert Participant

In Figure 6.1, the traffic complexity between AXM540 and TGW971 is evaluated. The vertical CAL value starts at 3, due to the initial overlap of their vertical flight profile, before dropping to a value of 1 at frame 4, corresponding to the instant that the expert participant cleared the descend to FL 350, which prevents the overlap of their vertical flight profile. The vertical separation between the two aircraft is maintained, resulting in a vertical CAL value of 1 till frame 42, when the aircraft crossed. For the lateral CAL value of AXM540 and TGW971, the value starts at 1, as the aircraft are far apart laterally. At frame 7, a lateral overlap between the aircraft first occurs, hence, causing the lateral value to increase to 2. This lateral overlap is present till frame 42, when the aircraft crossed laterally. Hence, the lateral CAL value maintains at value of 2, till frame 42. Moreover, it is also noted that the overall CAL value maintains at 1 in this duration.

In Figure 6.2, the aligned fixation peaks signature, which is used for monitoring enhancement, is computed for the expert participant on the aircraft pair-in-crossing, AXM540 and TGW971. Aligned fixation peaks are observed at frames 1 to 2, 4 to 5, 7 to 8, 19 and 37 to 40, thereby indicating the expert participant is monitoring both AXM540 and TGW971 for the crossing activity. The expert participant could likely be determining if the aircraft cross in frames 1 to 2, before issuing a descend to FL350 at frame 4. This corresponds to the same frame where vertical CAL value decreases from 3 to 1, representing that the participant could have assessed both AXM540 and TGW971 at the start, before issuing the command. At frames 7 to 8 and 19, the participant possibly recognised that the aircraft are closer spatially, thus executing a crossing monitoring behaviour to maintain awareness of the aircraft on the radar screen. Similarly, this also corresponds to the instant where the lateral CAL value increased from 1 to 2. From frames 37 to 40, it is likely that the participant is fixating on the both AXM540 and TGW971, to ensure that they cross safely.

Therefore, by integrating the traffic complexity and aligned fixation peaks signature, the monitoring strategy of the ATCO can be inferred accordingly. Results from the expert participant suggests that he is possibly managing this activity by deploying the strategy of maintaining vertical separation after identifying the aircraft-pair-in-crossing early. This is seen in the early aligned fixation peak being exhibited,

followed by the descend command to reduce the vertical CAL value. Upon maintaining a vertical separation between the aircraft pair-in-crossing, AXM540 and TGW971, the expert participant would just perform the crossing monitoring while maintaining his awareness of the aircraft pair-in-crossing. Targeted aids and alerts that are derived from the monitoring strategies can thus be created and deployed operationally to ATCOs, to better aid them in their crossing monitoring behaviour.

6.2. Overall Evaluation of Generic Flight Path Monitoring

Similarly, the generic flight path monitoring strategy using an expert participant's session on an aircraft pair, CPA810 and AXM890 while flying across the airspace sector is examined. This is achieved by computing traffic complexity across time and the RCG time entropy signature of the same expert participant on both selected aircraft. CPA810 and AXM890 crosses at waypoint OPULA at frame 177. AXM890 cruises at FL330 and enters the airspace at frame 62, while CPA810 descends from FL370 to FL330 and enters the airspace at frame 129. In this selected session, CPA810 and AXM890 were handed over to the adjacent sector at frame 196 and frame 192 respectively.

Using the proposed eye-hand movement model, the traffic complexity values for both CPA810 and AXM890 were evaluated from frames 129 to 192, as both aircraft were under the jurisdiction of the ATCO in this duration. The lateral and vertical CAL value of both aircraft from frames 129 to 192 can be seen in Figure 6.3. In addition, the RCG time entropy value is computed for the expert participant to represent the generic flight path monitoring behaviour for both CPA810 and AXM890, as seen in Figure 6.4 and Figure 6.5 respectively. It is important to note that the respective RCG time profile for CPA810 and AXM890 were plotted for different duration, due to the different flight duration of both aircraft present in the airspace.

Figure 6.3. Lateral and Vertical CAL plot of CPA810 and AXM890

Figure 6.4. RCG Time of CPA810 for 1 Expert Participant

Figure 6.5. RCG Time Profile for AXM890 of 1 Expert Participant

From Figure 6.3, the traffic complexity between CPA810 and AXM890 is evaluated. The vertical CAL value starts at 3, due to the initial overlap of their vertical flight profile, before dropping to a value of 1 at frame 155, corresponding to the instant that the expert participant cleared to the descend of CPA810 to FL 340, which prevents the overlap of their vertical flight profile. The vertical separation between the two aircraft is maintained, resulting in a vertical CAL value of 1 till frame 192, when the aircraft crossed. For the lateral CAL value of CPA810 and AXM890, the value starts at 1, as the aircraft are far apart laterally. At frame 152, a lateral overlap between the aircraft first occurred, hence, causing the lateral value to increase to 2. This lateral overlap is present till frame 192, when the aircraft crossed laterally. Hence, the lateral CAL value maintains at value of 2, till frame 192. Additionally, an overall CAL value of 2 is observed from frame 152 to 155.

Figure 6.4 shows the RCG time profile of CPA810 for the expert participant, containing 7 RCG and its RCG time entropy value is 1.586. This mean that the participant is monitoring regularly with the different RCG spaced at 9.6 frames on average. Similarly, for AXM890, the RCG time profile for this participant, containing 14 RCG with an RCG time entropy value of 2.376, is seen in Figure 6.5. This indicate that the expert participant performed generic flight path monitoring on AXM890

more frequently, as compared to CPA810, with the different RCG spaced at 9.3 frames on average. This higher number of RCG is likely a result of a longer flight duration of AXM890.

By integrating the evaluated traffic complexity and RCG time entropy of the expert participant, its monitoring strategy for the activity of generic flight path monitoring can be inferred. The RCG time entropy value of CPA810 and AXM890 were first normalised out of 100 frames, which was found to be 2.367 and 1.828 respectively. This meant that CPA810 was being monitored by the expert participant more regularly, despite the both aircraft having the same CAL value. One possible reason is the requirement for CPA810 to descend as specified in the scenario, thereby creating the need to be monitored more regularly. Therefore, it can be inferred that the expert participant adopts a strategy of monitoring an aircraft more often only when deemed necessary, as a higher RCG time entropy value is observed for the aircraft with a command issued. Such a strategy could likely aid in preventing phenomenon like over-focusing from occurring, thereby highlighting the expertise and experience of the expert participant.

6.3. Summary of Findings

The ability of the proposed eye-hand movement model in inferring the ATCO monitoring strategy is illustrated, using aircraft crossing with potential conflict and the generic flight path monitoring of aircraft. This is achieved by integrating the traffic complexity and corresponding eye signatures synchronously, to deduce the likely strategies that ATCOs deploy in managing these tactical monitoring activities. Such strategies from the ATCOs were not found in other eye-hand movement models.

Using one expert session, for the crossing monitoring activity, its eye signature of aligned fixation peak is matched to the respective tactical complexity value of the aircraft pair-in-crossing to better represent and understand the expert's monitoring behaviour, for monitoring enhancement within the same frame. Subsequently, the participant's monitoring strategy in dealing with different aircraft pairs-in-crossing can thus be deduced accordingly. Results suggest that the participant exhibited the aligned fixation peak signature for the purpose of maintaining vertical separation early and to keep awareness of the aircraft pair-in-crossing. These strategies inferred

from the proposed eye-hand movement model were found in other systems. This could pave the way for alerts catering to an ATCO's monitoring strategy to be developed operationally, thereby improving its effectiveness. In training, instructors could provide curated feedback to the trainees in order to speed up the training process.

Similarly, using one expert session, the generic flight path monitoring strategy is inferred by matching the RCG time entropy signature to the respective tactical complexity value of the selected aircraft. Results suggest that the expert participant likely deploys the strategy of monitoring an aircraft more often when a command needs to be issued. Therefore, operational aids can be provided to ATCOs in real time and in training, if any deviation in their generic flight path monitoring behaviour is found.

7. Chapter 7 Conclusion

7.1. Conclusion

This research work seeks to develop an eye-hand movement model for traffic complexity evaluation and monitoring enhancement for ATCOs, in their tactical control activity under different air traffic complexities. To do so, three individual components have been developed within the eye-hand movement model. These three individual components are found to be able to address the three main challenges of proper knowledge extraction and representation in ATC using both human and system operated functions, calculation of tactical air traffic complexity and the measurement of the perception and comprehension levels of ATCOs.

Different novel methods in the three components of the eye-hand movement model were established in this thesis, in order to better extract and represent knowledge of an ATCO in their tactical monitoring activity, under radar surveillance in area control. An innovative measurement was developed for proper knowledge extraction and representation, a new tactical complexity calculation method was presented, and three innovative eye signatures was created. An overall evaluation of the eye-hand movement model is then performed, where the monitoring strategy of the ATCO in two tactical monitoring activity is showcased.

An innovative measurement for the tactical control activity of ATCOs is successfully developed, using a real time eye tracking system. This system integrates two sets of activity data, human and system, based on the developed “Dynamic Data Alignment and Timestamp Synchronisation Model”, which is able to synchronise the timestamp of the eye and dynamic display data, align both of these data spatially, while taking into account changes in space and time of the dynamic display data.

Test results show that the proposed system can capture, and compute fixation count on any flight object (track or label) at a particular fixed crossing point, while showing variations in the monitoring behaviour between individual ATCO monitoring activity. This allows knowledge for a deeper understanding of an operator’s performance to be extracted with finer resolution, together with the good level of synchronisation, as

present ATC systems do not possess such capabilities in distinguishing the monitoring behaviour between ATCOs.

A new tactical complexity calculation method, CAL, for an instantaneous overall and regional score, based on user specified input location and time, has been presented. Likewise, the CAL-SAT model has also been successfully developed for the calculation of the CAL time profile between aircraft pair based on current instantaneous aircraft parameters. CAL determines the level of complexity from the state of overlap between the shapes of individual aircraft defined in the airspace, while the CAL time profile accounts for the dynamic traffic flow characteristics of the aircraft and its network characteristics. This allows the pairwise air traffic flow to be modelled and a tactical complexity analysis of the air transportation network to be established.

Validation of CAL indicates its consistency with other established complexity models, by producing the same complexity ranking order over a range of air traffic scenarios. Greater time predictability with respect to tactical complexity level and identification of critical time buffer zones between aircraft pair is also enhanced. This could pave the way for a useful planning tool to be developed, assisting watch managers in the allocation and duration of shift duties assigned to respective ATCOs.

Three innovative eye signatures were also presented in this thesis, for the three main tactical monitoring activity of managing aircraft crossing with potential conflict, aircraft switching frequency and the generic flight path monitoring of aircraft on the radar screen. Each signature utilises both the eye and hand signals of ATCOs, while mapping to the way that ATCOs approach and manage these tactical monitoring activities.

Aligned fixation peaks signature is developed for the management of aircraft crossing with potential conflict. This signature identifies instances when an ATCO perceives and comprehends the aircraft pairs-in-crossing through the alignment of its fixation peaks, and metrics to evaluate the aligned fixation peaks signature were derived. Results show that aligned fixation peaks signature can be used as a measure, to understand the variation in a participant's monitoring behaviour, due to angle and

proximity of crossings, as well as expertise level. In addition, it can be used as a measure to differentiate the expertise level of the participants and understand the differences in their crossing monitoring behaviour when managing aircraft crossing with potential conflict. A comparison between participant expertise levels show that experts are most likely to exhibit aligned fixation peaks, whereas a comparison among the crossing characteristics show that wide angle, independent and crossing points located at the corner of the screen are more difficult to perceive and comprehend. Hence, efforts can be dedicated to aiding ATCOs when managing aircraft flying across crossing points with such characteristics.

For managing the activity of aircraft frequency switch, a fixation-click count signature involving the ATCO's fixating on the track or label of incoming or outgoing aircraft, before clicking on respective commands within a specified duration based on operational requirements, is proposed. This signature can serve as a useful measure and possibly an alert indicator in capturing the perception and comprehension of ATCOs when performing the switch of aircraft frequency, for both 'UCO' and 'TOC' commands.

RCG time entropy signature is also developed for the management of the generic flight path monitoring of aircraft. This signature combines both fixation and 'mouse over' labels to identify the instances where participants are active in deliberately fixating on the aircraft during its flight, to maintain his awareness of it or to issue appropriate commands, for its generic flight path monitoring. The RCG time entropy signature is evaluated by calculating the information entropy value on the constructed RCG time profile, where a larger value represents a higher level of regularity and consistency of the RCGs throughout the flight duration of an aircraft.

Test results showed that the RCG time entropy signature is a suitable measure for understanding differences in an ATCO's generic flight path monitoring of aircraft, due to flight path configuration and expertise levels. Novice participants are found to lack the training and are less familiar in maintaining regular awareness on an aircraft's generic flight path. Such is due to novices monitoring less regularly both on flight path configuration 3 and for aircraft flying on a longer flight distance, as compared to other expertise levels. In addition, no significant difference in RCG time

entropy value was found between intermediate and experts at various flight path configurations. This indicates that intermediate participants are trained to the level of experts, as they could exhibit a similar level of regular awareness on an aircraft's generic flight path monitoring. Hence, the RCG time entropy signature can be used to differentiate the expertise level of ATCOs and also in the training of prospective ATCOs, where trainees can better monitor the generic flight path of aircraft, based on their flight path configurations.

Lastly, the proposed eye-hand movement model is applied successfully to two selected monitoring activities, by showcasing its ability in inferring the monitoring strategies of the ATCO. This is achieved by evaluating the tactical air traffic complexity, while enhancing the visual monitoring of ATCO. Test results show that traffic complexity and monitoring signature of ATCOs are integrated successfully within the same radar frame, synchronously, in real time. As a result, the monitoring strategies and desired monitoring behaviour of an ATCO can be deduced appropriately, thus enhancing their monitoring performance. This could pave the way for operational aids and alerts to be created both operationally and in training, for the visual monitoring activities of ATCOs.

7.2. Future Work and Recommendations

Several issues that could potentially progress the science have yet to be addressed in this research work.

In the development of an innovative measurement, the proposed “Dynamic Data Alignment and Timestamp Synchronisation Model” can be applied to other electronic surveillance fields or even approach and aerodrome control in ATC to further enhance its robustness. Furthermore, other non-intrusive physiological signals can also be incorporated in the system to apply more feature of measurement for new knowledge extraction and representation. A wearable eye tracker can also be used as the eye tracker, to test the feasibility of the model in extracting and representing knowledge of an ATCO's monitoring behaviour.

For the tactical complexity calculation method CAL and its time profile model, the CAL-SAT model, several recommendations can be made. Further instantaneous CAL

calculation can be made for aircraft flying in random trajectories. In doing so, a variation of CAL score can be extracted, and this can be studied further to improve the completeness of the CAL method. Furthermore, more intermediate levels of complexity can also be included in this CAL method, so as to further increase the granularity of tactical complexity.

In terms of the CAL time profile, an integrated CAL time profile for all the aircraft pairings present in the airspace can also be conducted, to deduce the overall CAL time profile of various airspace sectors. This can also further supplement the instantaneous CAL for the entire airspace sector. This would allow a holistic overview of the tactical complexity of the whole airspace sector over time, which could aid in the overall planning of the ATCO's shift and task. This CAL model can also be tested on ATCOs to derive the capacity of the airspace, from the perspective of the tactical complexity perceived by the ATCOs. Critical regions on the radar screen can also be identified.

In doing so, better planning can be made to factor the human limitations of the ATCOs in ensuring a safe and expeditious air traffic flow in the airspace. In addition, this CAL model can be also tested and interfaced with the runway capacity calculation, to determine its applicability and its effect on the airport's runway capacity. This would also allow proper capacity planning of the airport by taking into account the tactical complexity faced by the ATCOs due to the various flight schedules.

In the innovative eye signatures created in this research, a benchmark to grade the monitoring behaviour of ATCOs for the different tactical control activities can be performed, with the help of ATCO instructors or practitioners in this field. This would enable prospective ATCOs to be graded more objectively, based on these eye signatures. Furthermore, psychologists can also help to better interpret these signatures to provide more understanding of the ATCOs monitoring behaviour. Additional metrics can also be derived from these eye signatures, to allow a finer differentiation of the various ATCO expertise levels.

Similarly, these eye signatures can also be tested on other ATC control service, like approach and aerodrome control to enhance its robustness in capturing and evaluating the perception and comprehension levels of ATCOs. They can also be applied to other ATCOs from other regions of the world.

Apart from using eye and hand movement as physiological signals to derive these eye signatures, other physiological signals like brainwave or heart rate can also be included to fine tune these signatures further. This would enable added dimensions that would allow a better understanding of the perception and comprehension of ATCOs.

Similarly, for the monitoring strategies that could be inferred from the proposed eye-hand movement model, ATCO instructors could provide a better interpretation of an ATCO's monitoring strategy. This can help enhance the proposed eye-hand movement model further and better aids could also be derived. In addition, this model can also be applied to more tactical monitoring activities, to better understand and ascertain the relationship between tactical complexity and monitoring behaviour.

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9. List of Publications

Journal Published

1. Wee, H. J., Lye, S. W., & Pinheiro, J.-P. (2019). An Integrated Highly Synchronous, High Resolution, Real Time Eye Tracking System for Dynamic Flight Movement. *Advanced Engineering Informatics*
2. Wee, H. J., Lye, S. W., & Pinheiro, J.-P. (2018). A Spatial, Temporal Complexity Metric for Tactical Air Traffic Control. *Journal of Navigation*, 71(5), 1040-1054

Journal Submitted

1. Wee, H. J., Lye, S. W., & Pinheiro, J.-P. (2019). Tactical Complexity Time Profile Management Model for Air Traffic Controllers. *Transportation Science* [Check]

Journal on Embargo for Patent Application

1. Wee, H. J., Lye, S. W., & Pinheiro, J.-P. (2020). Aligned Fixation Peak Signature for representing Air Traffic Controllers' Crossing Monitoring Behaviour. *User Modeling and User-Adapted Interaction*
2. Wee, H. J., Lye, S. W., & Pinheiro, J.-P. (2020). Radar Command Group (RCG) Time Entropy Signature for representing Air Traffic Controllers' Generic Path Monitoring Behaviour. *IEEE Transactions on Human-Machine Systems*

Conference Published

1. Wee, H.J., S.W. Lye, and J.-P. Pinheiro, A Fixation-Click Count Signature as a Visual Monitoring Enhancement for Air Traffic Controllers, in *3rd International Conference on Intelligent Human Systems Integration Conference*. 2020
2. Wee, H.J., S.W. Lye, and J.-P. Pinheiro, Monitoring Performance Measures for Radar Air Traffic Controllers using Eye Tracking Techniques, in *10th International Conference on Applied Human Factors and Ergonomics*. 2019

3. H. J. Wee, F. Trapsilawati, S. W. Lye, C. H. Chen, and J. P. Pinheiro. (2017). Real Time Bio Signal Interface for Visual Monitoring of Radar Controllers. *ISPE International Conference on Transdisciplinary Engineering*.
4. H.J. Wee, S.W. Lye, and J.-P. Pinheiro. Real Time Eye Tracking Interface for Visual Monitoring of Radar Controllers. in *AIAA Modeling and Simulation Technologies Conference*. 2017.
5. H.J. Wee, S.W. Lye, and J.-P. Pinheiro, Computing Eye Tracking Metric for a Radar Display Using a Remote Eye Tracker, in *International Conference on Artificial Intelligence and Computer Engineering*. 2016, DEStech Publication, Inc: Future City Hotel Wuhan, China

10. Appendix A – Experimental Procedures

Experimental procedures to conduct the experiments on ATCO test subjects are presented

1. Briefing

- a. Participants are briefed on the equipment used for the experiment for familiarisation and the airspace of interest with the corresponding rules
- b. No information about the experiments are given, to prevent any form of anticipation, which may result in skewed or bias results.

2. Calibration

- a. The ATCO participant is checked on his seating posture.
- b. Calibration of the physiological signal measurement tools is performed, to ensure that the physiological data collected are not inaccurate due to inconsistencies

3. Experiment

- a. Throughout the entire experimental duration, ATCO participant will be carrying out his tasks by monitoring and making commands to the pseudo pilot for further action.
- b. Constant communication between the ATC subject and the pseudo pilot should be upheld throughout the entire experiment.
- c. Physiological signal measurement tool will record the physiological signals of the ATCO participants continuously, which are then transmitted to the post-processing server

4. Data Analysis

- a. Post-processing server will then perform the data analysis in real time

- b. These results are then extracted for deeper analysis

11. Appendix B – Sector 6 and its characterisation

Screenshot of Sector 6 of Singapore FIR is shown in Figure 11.1, which was taken from skyvector

Figure 11.1. Screenshot of Sector 6 (Skyvector)

Factors and levels possible, which are present in Sector 6 of Singapore's FIR

1. Angle of crossing

Angle of Crossing			
Medium (16 to 44 degrees)		Wide (45 to 180 degrees)	
Crossing Point	Angle (degrees)	Crossing Point	Angle (degrees)
ELGOR (E/E) & (W/W)	44	ELGOR (E/W)	136
MABAL (W/Cross)	36	URIGO (E, cross)	98
OMLIV (E, cross)	38	URIGO (W, cross)	82

	NOPAT (E, cross)	77
	NOPAT (W, cross)	103
	DAMOG (E, cross)	99
	DAMOG (W, cross)	81
	VISAT (E, cross)	55
	VISAT (W, cross)	125
	SUSAR (E, cross)	121
	SUSAR (W, cross)	59
	VEPLI	46
	UGPEK	67
	MUMSO (E, cross)	100
	MUMSO (W, cross)	80
	MABAL (E, cross)	144
	KILOT	54
	OPULA (E, cross)	82
	OPULA (W, cross)	98
	OMLIV (W, cross)	142

	DUBSA	140
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2. Number of airways before and after intersection

Number of airways before & after intersection				
2 to 1	2 to 2	2 to 3	3 to 3	4 to 4
DOLOX	NOPAT	MABLI	LUSMO	ENREP
	DAMOG			
	SUSAR			
	MUMSO			
	ELGOR			
	LEBIN			
	LIPRO			
	KILOT			
	MABAL			
	VISAT			
	DUBSA			
	OTLON			
	URIGO			
	UGPEK			
	VEPLI			

3. Airway traffic flow direction

Airway Traffic Flow Direction	
Single	Bi-directional
M763	N875
L642	M758
N891	M761
L629	
M771	

L635	
N892	
L644	
N884	
L625	

4. Airway Path

Airway Path	
Straight	Bend
NOPAT	DOLOX
DAMOG	MABLI
SUSAR	LUSMO
MUMSO	ENREP
ELGOR	
LEBIN	
LIPRO	
KILOT	
MABAL	
VISAT	
DUBSA	
OTLON	
URIGO	
UGPEK	
VEPLI	

5. Proximity of intersection

Proximity of Intersection	
Different ($X < d < 2X$)	Independent ($d > 2X$)

Intersection Points	Distance (NM)	Intersection Points	Distance (NM)
NOPAT,DAMOG	16.3	ENREP,NOPAT	44.1
OPULA,ONAPO	10.8	ENREP,VEPLI	60.4
URIGO,IDSEL	11.1	ENREP,TAXUL	70.3
URIGO,UGPEK	11.7	ENREP,UGPEK	75.5
		NOPAT,DOLOX	43.1
		NOPAT,VEPLI	52.2
		DAMOG,DOLOX	42.5
		DAMOG,DUBSA	27.5
		DAMOG,SUSAR	20.6
		SUSAR,MABLI	59.9
		SUSAR,MUMSO	21.8
		SUSAR,DUBSA	31.6
		MUMSO,MABLI	52.1
		MUMSO,ELGOR	21.3
		MUMSO,MABAL	25.2
		ELGOR,OPULA	33
		ELGOR,LEBIN	23.6
		ELGOR,MABAL	35.7
		LEBIN,LUSMO	53
		LEBIN,LIPRO	58.5
		OPULA,MABLI	45.9
		OPULA,LUSMO	34.3
		LIPRO,KILOT	32.2
		KILOT,MABAL	41.4
		KILOT,OTLON	21
		OTLON,VISAT	21.7
		URIGO,VISAT	24.8
		VISAT,DUBSA	26.6
		VISAT,MABAL	41.1

	DUBSA,UGPEK	39.7
	UGPEK,DOLOX	103.5

12. Appendix C – Full Descriptive Statistics for Table 5.6

Below is the table showing the full descriptive statistics for Table 5.6

		Aligned Fixation Peaks Metric	Novice	Intermediate	Expert
Layer 1	All crossing points	Total Number of Aligned Peaks	N = 188, M = 5.62, SD = 4.192	N = 176, M = 5.37, SD = 3.87	N = 411, M = 5.48, SD = 3.976
		Total Fixation Count	N = 188, M = 26.05, SD = 22.877	N = 176, M = 22.02, SD = 16.829	N = 411, M = 24.13, SD = 19.207
		Total Fixation Duration (ms)	N = 188, M = 23589.78, SD = 21211.24	N = 176, M = 25109.11, SD = 20765.97	N = 411, M = 22640.87, SD = 19649.25
Layer 2	Wide Angle	Total Number of Aligned Peaks	N = 131, M = 5.25, SD = 3.893	N = 127, M = 4.43, SD = 2.841	N = 301, M = 4.88, SD = 3.460
		Total Fixation Count	N = 131, M = 24.22, SD = 20.981	N = 127, M = 18.48, SD = 13.572	N = 301, M = 20.96, SD = 16.983
		Total Fixation Duration (ms)	N = 131, M = 21273.42, SD = 18792.86	N = 127, M = 19866.76, SD = 15076.60	N = 301, M = 19706.19, SD = 18100.50
	Medium Angle	Total Number of Aligned Peaks	N = 57, M = 6.46, SD = 4.74	N = 49, M = 7.80, SD = 5.00	N = 110, M = 7.12, SD = 4.775
		Total Fixation Count	N = 57, M = 30.25, SD = 26.456	N = 49, M = 31.18, SD = 20.741	N = 110, M = 32.80, SD = 22.139
		Total Fixation Duration (ms)	N = 57, M = 28913.33, SD = 25320.72	N = 49, M = 38696.45, SD = 26726.91	N = 110, M = 30671.20, SD = 21486.91
Layer 3	Close	Total Number of Aligned Peaks	N = 86, M = 5.64, SD = 4.099	N = 84, M = 4.60, SD = 2.875	N = 197, M = 5.08, SD = 3.726
		Total Fixation Count	N = 86, M = 27.05, SD = 22.506	N = 84, M = 19.06, SD = 14.496	N = 197, M = 22.47, SD = 18.699

		Total Fixation Duration (ms)	N = 86, M = 23406.83, SD = 19134.39	N = 84, M = 20968.36, SD = 15702.30	N = 197, M = 21433.34, SD = 20541.39
	Independent	Total Number of Aligned Peaks	N = 102, M = 5.60, SD = 4.290	N = 92, M = 6.08, SD = 4.495	N = 214, M = 5.84, SD = 4.168
		Total Fixation Count	N = 102, M = 25.21, SD = 23.262	N = 92, M = 24.72, SD = 18.372	N = 214, M = 25.65, SD = 19.582
		Total Fixation Duration (ms)	N = 102, M = 23744.03, SD = 22909.30	N = 92, M = 28889.80, SD = 23960.71	N = 214, M = 23752.47, SD = 18770.24
Layer 4	Center	Total Number of Aligned Peaks	N = 17, M = 5.06, SD = 3.473	N = 17, M = 4.29, SD = 2.932	N = 38, M = 5.39, SD = 2.656
		Total Fixation Count	N = 17, M = 22.41, SD = 17.08	N = 17, M = 17.94, SD = 12.557	N = 38, M = 22.16, SD = 11.686
		Total Fixation Duration (ms)	N = 17, M = 20511.82, SD = 16369.821	N = 17, M = 20946.76, SD = 18064.500	N = 38, M = 20818.50, SD = 11654.000
	Corner	Total Number of Aligned Peaks	N = 10, M = 3.20, SD = 1.613	N = 14, M = 4.29, SD = 1.939	N = 37, M = 4.11, SD = 2.366
		Total Fixation Count	N = 10, M = 11.20, SD = 18.26	N = 14, M = 14.71, SD = 7.290	N = 37, M = 16.97, SD = 12.121
		Total Fixation Duration (ms)	N = 10, M = 12130.60, SD = 977.58	N = 14, M = 14579.21, SD = 8221.790	N = 37, M = 15949.78, SD = 14491.890

13. Appendix D – Full Levene's F test result for homogeneity of variance on expertise level for Table 5.7

Below is the table showing the full Levene's F test result for homogeneity of variance on expertise level for Table 5.7.

Comparison of all Expertise Level		Aligned Fixation Peaks Metric	Levene's F test output
Layer 1	All crossing points	Total Number of Aligned Peaks	$F_{2,772} = 0.756, p = 0.470$
		Total Fixation Count	$F_{2,772} = 8.671, p = 1 * 10^{-4} \approx 0 *$
		Total Fixation Duration	$F_{2,772} = 0.756, p = 0.095$
Layer 2	Wide Angle	Total Number of Aligned Peaks	$F_{2,556} = 3.643, p = 0.027 *$
		Total Fixation Count	$F_{2,556} = 10.617, p = 1 * 10^{-5} \approx 0 *$
		Total Fixation Duration	$F_{2,556} = 2.155, p = 0.117$
	Medium Angle	Total Number of Aligned Peaks	$F_{2,213} = 0.160, p = 0.853$
		Total Fixation Count	$F_{2,213} = 1.548, p = 0.215$
		Total Fixation Duration	$F_{2,213} = 1.547, p = 0.215$
Layer 3	Close	Total Number of Aligned Peaks	$F_{2,364} = 2.554, p = 0.079$
		Total Fixation Count	$F_{2,364} = 7.907, p = 1 * 10^{-4} \approx 0 *$
		Total Fixation Duration	$F_{2,364} = 0.592, p = 0.554$
	Independent	Total Number of Aligned Peaks	$F_{2,405} = 0.453, p = 0.636$
		Total Fixation Count	$F_{2,405} = 2.487, p = 0.084$
		Total Fixation Duration	$F_{2,405} = 4.156, p = 0.016 *$
Layer 4	Center	Total Number of Aligned Peaks	$F_{2,69} = 2.464, p = 0.093$
		Total Fixation Count	$F_{2,69} = 5.897, p = 0.004 *$
		Total Fixation Duration	$F_{2,69} = 5.590, p = 0.006 *$
	Corner	Total Number of Aligned Peaks	$F_{2,58} = 0.528, p = 0.593$

		Total Fixation Count	$F_{2,58} = 1.342, p = 0.269$
		Total Fixation Duration	$F_{2,58} = 0.878, p = 0.421$

* indicates significance at 95% level

14. Appendix E – Full one way ANOVA or Welch F test results for Table 5.8

Below is the table showing the full one way ANOVA or Welch F test results for Table 5.7.

		Aligned Fixation Peaks Metric	One way ANOVA / Welch F Test Result
Layer 1: Generic Crossing Points	All crossing points	Total Number of Aligned Peaks	$F_{2,772} = 0.176, p = 0.838$
		Total Fixation Count	$F_{2,379.21} = 1.950, p = 0.144$ (Welch)
		Total Fixation Duration	$F_{2,772} = 0.919, p = 0.399$
Layer 2: Angle of Crossing	Wide Angle	Total Number of Aligned Peaks	$F_{2,273.66} = 2.011, p = 0.136$ (Welch)
		Total Fixation Count	$F_{2,270.66} = 3.583, p = 0.030$ * (Welch)
		Total Fixation Duration	$F_{2,556} = 0.376, p = 0.687$
	Medium Angle	Total Number of Aligned Peaks	$F_{2,213} = 1.020, p = 0.362$
		Total Fixation Count	$F_{2,213} = 0.250, p = 0.779$
		Total Fixation Duration	$F_{2,213} = 2.593, p = 0.077$
Layer 3: Proximity of Crossing	Close	Total Number of Aligned Peaks	$F_{2,364} = 1.751, p = 0.175$
		Total Fixation Count	$F_{2,179.72} = 3.936, p = 0.021$ * (Welch)
		Total Fixation Duration	$F_{2,364} = 0.416, p = 0.660$
	Independent	Total Number of Aligned Peaks	$F_{2,405} = 0.303, p = 0.739$
		Total Fixation Count	$F_{2,405} = 0.071, p = 0.931$
		Total Fixation Duration	$F_{2,182.96} = 1.757, p = 0.175$ (Welch)
Layer 4: Location of Crossing	Center	Total Number of Aligned Peaks	$F_{2,69} = 0.830, p = 0.440$
		Total Fixation Count	$F_{2,30.720} = 0.727, p = 0.492$ (Welch)
		Total Fixation Duration	$F_{2,28.529} = 0.003, p = 0.997$ (Welch)
	Corner	Total Number of Aligned Peaks	$F_{2,58} = 0.844, p = 0.435$
		Total Fixation Count	$F_{2,58} = 1.233, p = 0.299$
		Total Fixation Duration	$F_{2,58} = 0.369, p = 0.693$

* indicates significance at 95% level

15. Appendix F – Full Levene's F test result for homogeneity of variance on Crossing Characteristics for Table 5.10

Below is the table showing the full Levene's F test result for homogeneity of variance on crossing characteristics for Table 5.10.

Comparison of Crossing Characteristics	Expertise Level	Aligned Fixation Peaks Metric	Levene's F test output
Layer 2 (Wide vs Medium)	Novice	Total Number of Aligned Peaks	$F_{1,186} = 2.618, p = 0.107$
		Total Fixation Count	$F_{1,186} = 4.263, p = 0.040 *$
		Total Fixation Duration	$F_{1,186} = 7.095, p = 0.008 *$
	Intermediate	Total Number of Aligned Peaks	$F_{1,174} = 23.8, p = 1 * 10^{-6} \approx 0 *$
		Total Fixation Count	$F_{1,174} = 15.128, p = 1 * 10^{-4} \approx 0 *$
		Total Fixation Duration	$F_{1,174} = 22.317, p = 1 * 10^{-6} \approx 0 *$
	Expert	Total Number of Aligned Peaks	$F_{1,409} = 21.710, p = 1 * 10^{-6} \approx 0 *$
		Total Fixation Count	$F_{1,409} = 18.530, p = 1 * 10^{-5} \approx 0 *$
		Total Fixation Duration	$F_{1,409} = 11.838, p = 1 * 10^{-4} \approx 0 *$
Layer 3 (Close vs Independent)	Novice	Total Number of Aligned Peaks	$F_{1,186} = 0.252, p = 0.616$
		Total Fixation Count	$F_{1,186} = 0.002, p = 0.969$
		Total Fixation Duration	$F_{1,186} = 2.768, p = 0.098$
	Intermediate	Total Number of Aligned Peaks	$F_{1,174} = 11.350, p = 0.001 *$
		Total Fixation Count	$F_{1,174} = 5.445, p = 0.021 *$
		Total Fixation Duration	$F_{1,174} = 8.836, p = 0.003 *$
	Expert	Total Number of Aligned Peaks	$F_{1,409} = 3.591, p = 0.059$
		Total Fixation Count	$F_{1,409} = 2.574, p = 0.109$
		Total Fixation Duration	$F_{1,409} = 0.291, p = 0.590$

Layer 4 (Center vs Corner)	Novice	Total Number of Aligned Peaks	$F_{1,25} = 14.878, p = 0.001 *$
		Total Fixation Count	$F_{1,25} = 14.878, p = 1 * 10^{-5} \approx 0 *$
		Total Fixation Duration	$F_{1,25} = 14.878, p = 0.011 *$
	Intermediate	Total Number of Aligned Peaks	$F_{1,29} = 1.719, p = 0.200$
		Total Fixation Count	$F_{1,29} = 2.319, p = 0.139$
		Total Fixation Duration	$F_{1,29} = 12.074, p = 0.002 *$
	Expert	Total Number of Aligned Peaks	$F_{1,73} = 0.797, p = 0.375$
		Total Fixation Count	$F_{1,73} = 0.002, p = 0.962$
		Total Fixation Duration	$F_{1,73} = 0.111, p = 0.739$

* indicates significance at 95% level

16. Appendix G – Full one way ANOVA or Welch F test results to compare the effect of crossing characteristics for Table 5.11

Below is the table showing the full one way ANOVA or Welch F test results to compare the effect of crossing characteristics for Table 5.11.

Comparison of Crossing Characteristics	Expertise Level	Aligned Fixation Peaks Metric	One way ANOVA / Welch F Test Result
Layer 2 (Wide vs Medium)	Novice	Total Number of Aligned Peaks	$F_{1,186} = 3.318, p = 0.07$
		Total Fixation Count	$F_{1,88.00} = 2.320, p = 0.131$
		Total Fixation Duration	$F_{1,83.98} = 4.186, p = 0.044 *$
	Intermediate	Total Number of Aligned Peaks	$F_{1,60.307} = 19.652, p = 1 * 10^{-5} \approx 0 * (\text{Welch})$
		Total Fixation Count	$F_{1,64.498} = 15.775, p = 1 * 10^{-5} \approx 0 * (\text{Welch})$
		Total Fixation Duration	$F_{1,60.164} = 21.662, p = 1 * 10^{-5} \approx 0 * (\text{Welch})$
	Expert	Total Number of Aligned Peaks	$F_{1,152.783} = 20.330, p = 1 * 10^{-5} \approx 0 * (\text{Welch})$
		Total Fixation Count	$F_{1,158.265} = 25.908, p = 1 * 10^{-6} \approx 0 * (\text{Welch})$
		Total Fixation Duration	$F_{1,168.742} = 22.747, p = 1 * 10^{-6} \approx 0 * (\text{Welch})$
Layer 3 (Close vs Independent)	Novice	Total Number of Aligned Peaks	$F_{1,186} = 0.05, p = 0.946$
		Total Fixation Count	$F_{1,186} = 0.301, p = 0.584$
		Total Fixation Duration	$F_{1,186} = 0.012, p = 0.914$
	Intermediate	Total Number of Aligned Peaks	$F_{1,156.410} = 6.895, p = 0.01 * (\text{Welch})$
		Total Fixation Count	$F_{1,170.495} = 5.188, p = 0.024 * (\text{Welch})$
		Total Fixation Duration	$F_{1,158.333} = 6.839, p = 0.01 * (\text{Welch})$
	Expert	Total Number of Aligned Peaks	$F_{1,409} = 3.773, p = 0.053$
		Total Fixation Count	$F_{1,409} = 2.837, p = 0.093$
		Total Fixation Duration	$F_{1,409} = 1.430, p = 0.232$

Layer 4 (Center vs Corner)	Novice	Total Number of Aligned Peaks	$F_{1,24.149} = 3.556, p = 0.071$ (Welch)
		Total Fixation Count	$F_{1,23.277} = 5.647, p = 0.026$ * (Welch)
		Total Fixation Duration	$F_{1,24.968} = 2.775, p = 0.108$ (Welch)
	Intermediate	Total Number of Aligned Peaks	$F_{1,29} = 1 * 10^{-5} \approx 0, p = 0.993$
		Total Fixation Count	$F_{1,29} = 0.721, p = 0.403$
		Total Fixation Duration	$F_{1,23.251} = 1.688, p = 0.207$ (Welch)
	Expert	Total Number of Aligned Peaks	$F_{1,73} = 4.897, p = 0.03$
		Total Fixation Count	$F_{1,73} = 3.557, p = 0.063$
		Total Fixation Duration	$F_{1,73} = 2.577, p = 0.113$

* indicates significance at 95% level