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Real-Time Visual Analytics Interfaces to Strengthen Human-Automation Collaboration

Elmira Zohrevandi

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REAL-TIME VISUAL ANALYTICS INTERFACES TO STRENGTHEN HUMAN-AUTOMATION COLLABORATION

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Abstract

Automation in today's world supports human operators to accomplish several tasks in limited time. With more advanced automation and autonomous systems, the humans' role is shifting from hands-on operational tasks to supervisory tasks. In complex environments such as air traffic control, supervisory tasks become difficult to manage during unexpected situations as the operator needs to have a clear understanding of various resolution strategies and their consequences and make decisions about them in a limited amount of time (i.e. within a couple of minutes). In such environments, interface designers must carefully consider how information should be presented to the operators. An improper way of presenting information could, wastefully consume operators' cognitive resources resulting in inefficient decision-making and an increased risk of failure.

By designing ecological visual analytics interfaces, this thesis addresses the problem of real-time decision-making in the domain of air traffic control. The aim of this thesis has been to apply ecological design theories to the design and evaluation of visual representations to better support controllers' analytical capabilities and decision-making. Four novel visual analytics interfaces were designed, developed, and tested over the course of this research project. To understand how the designed visual representations affected the operators' decision-making processes, evaluation studies with air traffic controllers as well as novices without ATC experience were conducted for two of the designed interfaces and the results were analyzed.

The contribution of this thesis to the field of air traffic control and visualization design is fourfold. First, the thesis contributes knowledge on what information should be visualized and how, to achieve functional goals of conflict detection and resolution task of air traffic control. Second, evolved through a series of design studies, a final interactive visual analytics interface is proposed that visualizes information about the available solution space for solving conflict situations between airborne traffic and the traffic complexity. The interface supports controllers' decision-making process for resolving conflicts and ability to reduce the traffic complexity. Third, the method developed for evaluating the interface designs contribute with knowledge on how interfaces tailored to safety-critical systems can be tested. Fourth, findings show that the integration of ecological interface design with the development of visual representations can shape novice and expert operators' decision-making towards domain-specific functional goals, while allowing them to follow their own problem-solving strategies.[1]

[1]Parts of the text in the *Abstract* is based on the following publication: **Zohrevandi, E.** (2019, September). *Visualization of complex situations to strengthen human-automation collaboration.* In Proceedings of the 31st European Conference on Cognitive Ergonomics (pp. 14-18).
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Additional Publications

- **Zohrevandi, E.**, Polishchuk, V., Lundberg, J., Svensson, Å., Johansson, J., & Josefsson, B. (2016). Proceedings of the 6th SESAR Innovation Days. EUROCONTROL. ISSN 0770-1268. Delft, 8-10 November.

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- **Zohrevandi, E.** (2019, September). *Visualization of complex situations to strengthen human-automation collaboration*. In Proceedings of the 31st European Conference on Cognitive Ergonomics (pp. 14-18).

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Keywords

- Abstraction hierarchy
- Angular timeline visualization
- Air traffic complexity
- Air traffic control
- Air traffic controller
- Conflict detection and resolution
- Ecological interface design
- Focus context visualization
- Human–automation collaboration
- Human–computer interaction
- Information visualization
- Interaction
- Rate of climb or descent
- Research through design
- Safety-critical systems
- Visual analytics
- Visualization
- Visualization design and evaluation methods
- Work domain analysis

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List of Abbreviations and Acronyms

AH Abstraction Hierarchy

ATC Air Traffic Control

ATCo Air Traffic Controller

ATL-Viz Angular Timeline Visualization

ATLViz-cplx Angular Timeline Complexity Visualization

CARD Conflict and Risk Display

CD&R Conflict Detection and Resolution

EID Ecological Interface Design

HDG Heading

HSS Heading Solution Space

HTA-Viz Heading Time Altitude Visualization

RAD-Viz Radial Time Visualization

ROCD Rate of Climb or Descent

TA Time-Altitude Display

VA Visual Analytics

WDA Work Domain Analysis

1

Introduction

Safety-critical automated environments are characterized by the urgency and level of complexity involved with unexpected events (e.g. changes in weather, turbulence, poor transfer of control, and poor coordination at crossing areas of control; Malakis and Kontogiannis 2013; Kontogiannis and Malakis 2013) that occasionally occur in the system. These types of environments, which are becoming increasingly common, are found in industrial domains such as air traffic control (ATC) and societal domains such as home health, emergency response and ambulance dispatch. The core characterizing attribute of these environments is limited and sometimes insufficient time to act. Operators of such environments regularly confront urgent situations and make decisions efficiently within a limited amount of time. To make timely efficient decisions, the operator requires access to an appropriate level of information presented in a way that supports rapid understanding of the situation.[1]

ATC is an example of a safety-critical automated environment where operators are being exposed to rich information every day. En-route ATC environments involve

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aircraft flying at high speed and altitudes. ATC systems control many aircraft coming from various directions with various speeds and altitudes, heading to different destinations. Consequently, air traffic controller (ATCo)s can not freely halt processing such complex dynamic information to take a short rest (Gronlund et al., 1998).

In currently used automated systems the amount of information to be processed by the operators accumulates, making them increasingly complex (Endsley and Kiris, 1995; Ortner et al., 2022; Li and Harris, 2007). Early studies have shown that automation-induced complexity leads to more cognitive load and poor performance associated with loss of situation awareness (Endsley and Kiris, 1995). Therefore, keeping the human in control in a way that the system could benefit from the human operator's expertise during unexpected events is a vital step to manage complexity in high-stake automated environments. Another pivotal step is to support human performance by visualizing the information required to make decisions effectively. Human decision-making is central to visualization design (Munzner, 2014; Ware, 2019). Visualization supports the decision maker in understanding the data and interacting with it, unraveling unclear goals and forming a "mental model" that will finally lead to an informed choice (Spence, 2014). Ward et al. (2015) find decision-making to be the only reason to why visualizations exist; to support the decision maker in managing the information overflow.

Despite decision-making being central to visualization design, the analysis study of Dimara and Stasko (2021) shows that the visualization task taxonomies proposed in the field of visualization, rarely cover decision tasks. Furthermore, various task abstraction techniques presented by visualization researchers are usually designed based on the task flow followed by specific users. Moreover, the visualization design models do not describe the criteria for defining visualization tasks correctly (Marai, 2017). This indicates a lack of focus in the field of visualization on how to design interface functions by considering human factors and human-centered cognitive capabilities independent of specific users within specific contexts (Tory and Moller, 2004; Dimara and Stasko, 2021).

In an attempt to facilitate decision-making for human operators, this thesis bridges the gap between the field of cognitive science and visualization by integrating the ecological interface design (EID) approach into the design of visual analytics (VA) interfaces. The EID approach studies the human operator's work domain. In particular, ecological interfaces discover and reveal the constraints of the environment imposed on the operator, unraveling the relationship (links) between these constraints. With such characteristic, EID-based interfaces can enhance understanding of the domain complexities. Furthermore, these interfaces expedite data extraction for users aiming to support productive thinking especially during complex and unfamiliar situations (Borst et al., 2014).

The next section describes the research problem specific to the domain of ATC that this thesis addresses. Section 1.2 describes the technique that has been integrated into the design of visual representations as a proposed solution to the described problem. Section 1.3 describes the research through design approach that emerged naturally from the studies conducted with expert ATCos. Section 1.4 describes the specific research question and challenges faced. Section 1.5 presents the scope and assumptions made throughout the studies. And finally, Section 1.6 outlines how each study conducted connects to the research problem and research goal of the thesis.

1.1 Problem definition

ATC is managed successfully when two goals of *safety* and *efficiency* are considered simultaneously by the ATCo in real-time. Safety in airspace is maintained through the ATCo enforcing traffic separation rules while efficiency is maintained by expediting the flow of traffic. Even though current automated airborne collision avoidance systems on-board provide additional safety by warning pilots of the presence of other aircraft that may present a threat of collision, it is the responsibility of the ATCo to foresee the possibility for conflicts, plan ahead and prevent them. Today ATCos are supported by the automated medium-term conflict detection (MTCD) system, which processes flight data to warn the ATCo of potential conflicts. MTCD predicts conflicts up to 20 minutes ahead of occurrence. The information presented to the ATCo includes detection and notification of probable loss of separation between an aircraft pair. Because of parallel and time-critical task demands, ATCos are required to adapt their decision-making to the highly dynamic and complex ATC environment (Sheridan, 2002). While current automated systems warn ATCos of probable conflicts, they do not support ATCos in decision-making, which becomes challenging at unexpected events. Therefore, at an unexpected situation, it is the responsibility of the ATCo to analyze different resolution strategies, evaluate them and initiate an action order to resolve the conflicts. Operating in such complex situations imposes increased mental workload on the ATCos. Conflict detection and resolution (CD&R) is a core task of an ATCo. Mathematical models have shown that, in addition to CD&R, ATCos' workload is driven by the airspace traffic complexity as well. At dense traffic conditions, the dynamic nature of traffic patterns adds up to the uncertainty and complexity of the situation resulting in higher workload for ATCos.

A possible approach to decrease ATCos workload would be to extend the automation support range from normal predicted situations to unexpected events; by designing a system which assists ATCos in their decision-making process by presenting relevant information about: (a) the potential conflicts, and, (b) how different resolution strategies affect each individual aircraft flight trajectory as well as the whole traffic complexity. As such, the research questions this thesis is concerned with are:

Problem definition

1. What information needs to be visualized to support ATCos in CD&R task?
2. What information needs to be visualized to support ATCos in managing traffic complexity?
3. How should the information be integrated so that ATCos' decision-making in CD&R task as well as managing traffic complexity is facilitated?

1.2 Ecological interface design

EID was first introduced by Rasmussen and Vicente (1989) specifically for complex, dynamic and real-time systems. EID applies an ecological approach to the interface design, which means it prioritizes operators' environment ("ecology") over the individual operators themselves by focusing on the constraints the work domain imposes on the operator. This characteristic differentiates the EID framework from user-centered design methodology making it independent of specific tasks performed by specific end users (Vicente, 2002).

The aim of EID is to support operators' perception and control at the cognitive level they choose to perform. To do so, the designer must create a graphical ecological environment, where the system's functional boundaries and operational constraints are mapped onto the interface. Such mapping across the interface should be able to simultaneously support the operators' switching between different levels of control, movements, acts and plans (Rasmussen and Vicente (1990)). Another aim of the EID framework is to reduce mental workload and support the operator with knowledge-based reasoning. Therefore, when the EID framework is used, it is expected that users' performance for both expected and unexpected events in complex systems, is improved. Even though EID is a framework designed for providing support to operators in managing unexpected events of complex systems, it has also proved useful in training users to become experts (Lintern and Naikar, 2000; Hilliard, 2007, 2012; Smith et al., 2019; Burns and Hajdukiewicz, 2017). EID consists of two steps which are explained next.

EID first step

The first step of EID describes "the domain's complexity" and specifies the solution space boundaries of the environment, outside of which the system's functional goals will be violated. This step is called the work domain analysis (WDA) and is described by Naikar (2013) as "the functional structure of the environment of actors". The WDA technique is maintained by applying an abstraction hierarchy (AH) as introduced by Vicente and Rasmussen (1992), which is a form of representing constraints in a work domain independent of the system's state. The AH is a hierarchical description of the operator's environment structured by means-end relationships between the joint levels. Several hierarchical task abstraction models are proposed in the field of visualization (Stary, 2000; Amar et al., 2005; Gotz and Zhou, 2009; Streit et al., 2011; Brehmer and Munzner, 2013; Munzner, 2014). In all these models, the task abstraction relies on observing what the operator does to meet their needs. A problem that may occur in this approach is that the designed system may work improperly if the user tasks are ill-defined. Despite the aforementioned models, the AH relies on specifying what functions need to be supported to shape operators' behaviour within the system boundaries. The solution boundaries are defined through a hierarchical requirement analysis governed by the laws of physics. That makes the EID-based interfaces independent of specific tasks performed by specific end users.

The WDA technique has been used both in the context of developing EID-based interfaces and also for resolving interface issues. In the context of EID, WDA has been performed to improve energy efficiency monitoring (Hilliard and Jamieson, 2007, 2014), railway driving performance (Read et al., 2021), road (Baber et al., 2019) and maritime (Van Dam et al., 2006; Morineau et al., 2009; Fay et al., 2018) traffic management, medical engineering (Kwok and Burns, 2005; McEwen et al., 2012; Li et al., 2014), aviation (Amelink et al., 2005; Borst et al., 2007; Van Dam et al., 2008; Borst et al., 2008, 2010; Ellerbroek et al., 2011, 2013) and in ATC (Lodder et al., 2011; Klomp et al., 2014; Mercado Velasco et al., 2015; Beernink et al., 2015; Borst et al., 2017; Ellejmi et al., 2018)

In the context of resolving interface issues, Mumaw et al. (2000a,b); Xu (2007) performed WDA and identified gaps and actions needed to resolve pilots' flight deck automation issues.

EID second step

The second step of EID communicates the information to the operator by giving a "form" to the interface. The form of the interface should allow the operator to encode the information at the lowest possible cognitive processing level. In the EID framework, this step is maintained through Vicente and Rasmussen (1992)'s skills, rules, knowledge taxonomy.

A known limitation associated with EID is that it does not provide design guidelines for the interface "form", creating a gap between EID's first and second step (Vicente, 2002; Burns and Hajdukiewicz, 2004; Van Paassen et al., 2005; Borst et al., 2007; Van Dam et al., 2008). To enhance the ecological aspects of the interface, this thesis relies on visualization research to explore the appropriate "form" of VA interfaces designed for safety-critical systems and presents guidelines for their design.

1.3 Research through design

In complex situations where a number of parameters are involved in fostering the change dynamics, defining the problem boundaries can become challenging. One way to deal with such conditions, is to create one possible solution to facilitate understanding of different parameters' impact on the situation dynamics. Research-through-design is a framework in which the designed artifact and the research activities are always tight to each other (Gaver, 2012). The knowledge for designing the artifact is gained through the iterative process of creating one solution, framing the problem, testing the solution and re-framing the problem and creating a better solution (Zimmerman and Forlizzi, 2008; Gaver, 2012). The design and implementation process of the VA interfaces developed throughout this thesis involved design of the information to be visualized as well as the interactive features of the visual representations. To design the information, this thesis applied the WDA technique (the first step of the EID framework). The interactive features and functionalities of the interfaces were designed and developed based on the knowledge gained through the design activities, mainly from the discussions conducted with expert ATCos. The various versions of the prototypes created through the whole iterative design process became the analysis object (research artifact) of discussion sessions conducted with ATCos. These research activities enhanced the interactive features of the re-designed VA interface and provided knowledge regarding alternative visual representations to present the same information. To make the research-through-design contributions of the work accessible to the design researchers (Zimmerman et al., 2010), various research activities conducted with ATCos including the questions asked, the scenarios illustrated on the prototypes and the ATCos' responses to the questions are documented throughout this thesis.

1.4 Research goal and challenges

The main goal of this thesis was to apply WDA and information visualization techniques to design of VA interfaces to support operators of safety-critical domains in decision-making. In an attempt to reach this goal, this thesis focuses on the ATC domain. To answer the research problem formulated in Section 1.1, this thesis aims to:

Thesis goal

- Apply the WDA technique to the CD&R task of ATC.
- Design and evaluate VA interfaces that improve ATCos' decision-making with respect to maintaining safety and managing traffic complexity as compared to a simplified version of currently used ATC displays.

The thesis adopts an ecological approach to explore what information needs to be visualized to facilitate operators' understanding of the situations as well as analysis of possibilities. To identify appropriate and effective ways of communicating the information to the operators, this thesis explores new representations based on established visualization techniques to "form" the VA interfaces.

By developing new design concepts with the aim of making constraints and complex relationships in the system perceptually evident to the operator, more of the operators' cognitive resources can be devoted to problem-solving and decision-making. In addition, this opens new opportunities for the operator to visually interact with the automated tasks to supervise, control and when necessary interfere with automated real-time processes. As an emergent property of such approach to the design of VA interfaces for highly automated complex environments, it is expected that operators' efficiency (time to accomplish tasks) and workload are enhanced.

The ecological approach adopted in this thesis for mapping ATCos' CD&R task, implied a number of challenges. The first challenge was the application of the WDA technique itself to the CD&R task of ATC. Previous works in the field of aviation and ATC, had mainly focused on conducting WDA on aircraft motion problems. Even though aircraft are complex objects with unpredictable behaviour, due to uncertain weather and traffic conditions, precise modelling of their motion dynamics is possible using laws of physics. To perform WDA on ATCos' CD&R task, however, one needs to study the separation process and resolution strategies ATCos perform in various traffic situations. Very few studies in the literature have studied ATCos' problem-solving processes in details.

The second challenge of this thesis was to design the most appropriate "form" of the VA interfaces not based on own imagination but based on visualization-based research and reasoning. To this end, this thesis attempted to incorporate both the outcome of previous visualization research studies and expert ATCos' opinions obtained from participatory design activities into the development of the final "form" of the designed VA interface.

The third challenge was to design experimental studies for evaluating users' interaction with the designed interfaces and measure their decision-making processes in visualization tasks. Designing such studies was challenging mainly because, prior to this thesis work, no other studies in the field of visualization had been performed to design of VA interfaces tailored to real-time decision-making of ATCos. Therefore, measures for assessment of ATCos decision-making process were not defined prior to this thesis.

1.5 Thesis scope and assumptions

The limitation of the current thesis is that it can not cover all aspects of neither the ATC tasks nor aircraft motion.

1.5.1 Scope

This thesis first studies and practices application of WDA (the first step of the EID framework) on the CD&R task of ATC to support ATCos in their decision-making process. In response to: "what information needs to be visualized", the WDA principles are applied to determine which ecological constraints (imposed by the environment) shape ATCos' CD&R task and how they are linked to each other. Second, in response to: "how should the information be visualized", the thesis studies and applies visualization techniques to develop VA interfaces to support ATCos in CD&R as well as in managing the traffic complexity. With regard to the designed visual representations, the thesis does not aim to explore all possible alternatives, but proposes solutions for the requirements obtained from the WDA. Third, by testing the proposed visual representations in the domain of ATC, the thesis presents general design guidelines that can be applicable to other safety-critical domains. Table 1.1 specifies how the research questions formulated are addressed in each publication.

Four different designs are discussed throughout this thesis: 1) A VA interface, called HTA-Viz to support ATCos in CD&R. The novel characteristic of HTA-Viz is that it features a focus+context time-altitude display, which emphasizes aircraft in conflict, the vertical relationship between them and their urgency; 2) ATL-Viz which was designed based on HTA-Viz, addresses the limitation of currently used ATC displays in two aspects. First, the interface supports ATCos in probing "what-if" and "what-else" functionalities with respect to solutions to conflicts. Second, by enhancing the composite glyph representation of HTA-Viz, ATL-Viz visualizes how horizontal and vertical solution strategies affect conflicting situations. 3) RAD-Viz which is an alternative VA interface to ATL-Viz. RAD-Viz was designed to explore how a different way of visualizing of the temporal domain affects ATCos understanding of the conflict situations as well as their performance. and, 4) a finalized version of

Table 1.1: Thesis research questions addressed in the publication appended to this thesis

Thesis scope

Design step	Aim	Study
Applying the WDA technique	Derivation of the information that needs to be visualized to support ATCos in CD&R task	Paper I and III
Applying visualization techniques and evaluation	Exploring how should the information required for performing CD&R task be visualized	Paper I and II
Evaluation and proposing design guidelines	Testing VA interfaces designed for CD&R task	Paper II
Conducting a discussion session with an ATCo	Derivation of the information that needs to be visualized to support ATCos in managing traffic complexity?	Paper IV
Applying visualization techniques and evaluation	Exploring how should the information required for managing traffic complexity be visualized	Paper IV

ATL-Viz which not only presents the solution space to conflicts but also supports ATCos in managing the traffic complexity.

1.5.2 Assumptions

First it is assumed that pilots always comply with ATCos instructions. Consequently, it is assumed that there is no delay from when ATCos clearance is given to executing the clearance. In other words, it is assumed that ATCos have the full authority to separate aircraft to resolve conflicts.

Second, it is assumed that ATCos perform single actions to resolve multi-aircraft conflicting situations (i.e. more than two aircraft involved in a conflict). In other words, ATCos' multi-aircraft resolution strategies are neglected. This means that ATCos are assumed to perform one action at a time to resolve a conflict, with additional actions allowed to take place afterwards, one step at a time.

Third, limitations regarding aircraft performance characteristics on applied resolution strategies are neglected. In other words, it is assumed that ATCos' resolution commands will be achieved by aircraft immediately regardless of the aircraft type or the altitude at which they are flying. In reality however, various aircraft types can apply heading changes requested by ATCos with different rates, i.e. some aircraft turn with a rate of 3 degrees per minute while some others can turn slower. Similarly, aircraft rate of climb or descent (ROCD) varies depending on the aircraft type and the altitude at which they are flying. However, in my designed interfaces in this thesis the aircraft turns to the new heading or flies at the cleared flight level immediately after the ATCo issues a command.

Fourth, when modeling the aircraft motion, linear kinematic equations are derived. In doing so, it is assumed that aircraft maintained constant speed during flight unless the ATCo ordered a change. Fluctuations in airspeed, and aircraft performance characteristics are also neglected.

Fifth, constraints imposed by weather (e.g. wind effects), sector geometries and terrain on ATCos' tasks and aircraft motion are not considered in this thesis.

1.5.3 What this thesis does not contain

While the thesis practices an ecological approach towards the design of VA interfaces for supporting ATCos, the approach itself is not the subject of investigation. The thesis does not aim to compare or evaluate different approaches that could have been taken to discover "what information needs to be visualized" part of the formulated research problem. The theoretical foundations of the WDA technique applied on ATCos' CD&R task are considered as axioms throughout this thesis. In this regard, the thesis only focuses on adjusting and applying WDA on ATCos' CD&R task and designing visual representations based on the outcome of the WDA.

Considering all the assumptions mentioned in Section 1.5.2, this thesis does not aim to produce a fully functional interface for ATCos, but to present a conceptual approach to design visual representations to support ATCos' decision-making with respect to CD&R task. The conceptual approach proposed, involves the entire iterative design process that comprises a series of steps, including conducting the WDA, the visualization research aspects of the study, the research-through-design activities performed to generate knowledge about interactive features and the evaluation studies conducted to test the visual representation.

1.6 Thesis outline

This thesis contains five sections including Section 1 (the current section) and four other sections.

Section 2: Related Work reviews previous works done in the field of visualization and cognitive science engineering related to current work with respect to five aspects. First, previous VA interfaces developed to visualize various characteristics of the spatio-temporal data are reviewed. Second, methods proposed in the field of visualization for derivation of interface functions are reviewed. Finally, previous real-time decision support concepts developed for ATCos are presented.

Section 3: Summary of contributions details the contribution of the author in the prototype development as well as conducting the design and evaluation study performed in each of the articles included in this thesis.

Section 4: Conclusion discusses the results obtained from all design studies conducted. Taken together the whole iterative design process conducted in this dissertation, this section reflects upon the research problem formulated in Section 1.1 and final conclusions are presented.

Section 5: Discussion and Future Work reflects on the critical aspects of the methodology acquired and the designed visual encodings. Study limitations are discussed and future research directions are presented.

2

Related Work

In the era of information, human's ability in collecting large amounts of data has surpassed their ability in analyzing the data (Thomas and Cook, 2006; Keim et al., 2010), leading to the information overload problem. From a visualization perspective, visual representation techniques aim to facilitate data extraction for users. From a data analysis perspective, statistical or logical techniques aim to strengthen analysis processes for the users. However, purely analytical or purely visual approaches can not efficiently support humans in analyzing complex data (Keim et al., 2008). This led to the creation of the VA discipline (Ebert et al., 2010; Chen et al., 2012), which uses visualization and interaction techniques to enable humans to gain insight from complex data, discover patterns, reason analytically and make decisions effectively (Thomas and Cook, 2006; Keim et al., 2008). The aim in VA interface design is to support users in the decision-making process (Tominski and Schumann, 2020; Ware, 2019).

VA interfaces can be characterized based on the type of data visualized i.e. *spatio-temporal data*, *multivariate data*, *textual data* or *graph and network* data (Sun et al., 2013). This thesis aims to explore the use and benefit of VA approaches applied to the category of spatio-temporal data to support ATCos' decision-making in managing conflicts between aircraft. Three lines of research have been defined and explored in this thesis. First, aircraft movement data was analyzed, effectively transformed and visualized. Second, appropriate interfaces were designed to enable ATCos to understand the current conflict situations and make decisions for their resolutions. Finally, these interfaces were tested and validated in action. This section includes three subsections covering related research concerning each of the three focuses defined above.

In Section 2.1, I first review VA interfaces designed to visualize air transportation data. Then in Section 2.2, I first highlight the importance of task abstraction step in the visualization design process. Second, I review the task abstraction methods developed in the field of visualization for deriving interface functions and then discuss common weaknesses. Finally, since this thesis aims to facilitate decision-making for ATCos, in Section 2.3, I review previous ATC decision-support interfaces designed and discuss their limitations.

2.1 Visual analytics of air transportation data

Spatio-temporal data are inherently complex because of the large quantity and heterogeneity of the objects populating them or the events happening in them. To deal with such complexity, the domain experts' knowledge and experience within a specific context needs to be considered (Andrienko et al., 2013). Therefore this section only reviews previously designed interfaces that have particularly focused on visualization of air transportation data. To facilitate visual analysis of deviations, and analyzing detailed flight characteristics of individual aircraft trajectories among a large number of flights, various visualization techniques have been explored. Hurter et al. (2009) designed an interface, where an ATC expert could detect errors and uncertainties in the recorded data and in-depth analyze individual trajectories by spreading interesting parts of the data across separated views. Buschmann et al. (2014) applied color-mapping, texturing and animation technique to visualize various features of flight trajectories. Buchmüller et al. (2015) designed an interface with coordinated-views, where in addition to detecting deviations, users could extract insight about impact of flights on airports as well as predicting local weather impact on flights. Hurter et al. (2019) designed an immersive analytics environment, where users could interact and gain insight about aircraft trajectories in 3D space. To explore the temporal evolution of specified parts of aircraft trajectories over locations of interest, Hurter et al. (2011) proposed a focus+context interactive lens concept and Andrienko et al. (2018) proposed a relevance-aware analytical clustering technique.

While the aforementioned VA interfaces focused on addressing the large quantity aspect of the spatio-temporal air traffic data, in this thesis, I focus on the complexity aspect that corresponds to events that happen in the air traffic data in real-time. These events include emergence of complex traffic patterns and loss of separation occurrences between aircraft.

With respect to emergence of complex traffic patterns, visualization of air traffic complexity has been so far limited to post-analysis of historic data such as density maps of spatial data collected over several hours (Delahaye et al., 2004; Andrienko et al., 2018) and visualizing conflicting parts of trajectories (Durand et al., 2018). In this thesis, however, I propose visualization concepts which show information about emerging complex patterns in near future and present possible complexity-reduction solutions in real-time.

2.2 Task abstraction methods for visual analytics interfaces

Visual interfaces are designed to enable users to perform tasks and achieve a certain goal. As such, an interface is only useful if it enables its users to perform these tasks effectively. This puts weight both on the definition of the tasks themselves as well as the design of the interface components. For a long time the outcome of theoretical research in visualization design studies, remained limited to proposing guidelines for designing interfaces. Tory and Moller (2004) argued for consideration of human-factors into visualization processes to promote system's usefulness through better understanding of the data. Shneiderman and Plaisant (2006) reviewed the methods used in the field of HCI and proposed guidelines for evaluating the effectiveness of interfaces designed for expert users. He emphasized that a visualization designer must investigate whether the users' goals are achieved when working with the designed interface. Wassink et al. (2009) called for design guidelines where various types of users performing context-specific tasks to reach different goals are differentiated. In 2009, Munzner proposed a design model called "the nested model" and described the visualization design process in four layers i.e. *problem domain characterization*, *data and task abstraction*, *visual encoding and interaction design* and *algorithm design* (Munzner, 2009). The model prescribes the designer, evaluation techniques to identify threats to validate each design step they follow and emphasizes the importance of the output to one level being the input to the next. While all the aforementioned models highlight higher-level knowledge and awareness about the steps in the visualization design process, they do not describe how each step should be followed. Munzner (2009) calls the task abstraction stage as "hardest to get right" and warns the designer that a mistake made in the task abstraction stage can not be compensated by neither the perfect visual encoding nor the perfect algorithm design. Such mistake will lead to creation of a visualization system that will not solve the intended problem. Therefore, in this thesis I have tried to choose the most appropriate technique for derivation of tasks that need to be supported by a real-time VA interface designed for ATCos.

One challenging aspect of the task abstraction phase is the distinction between the means and ends of a task performed by the user (Sedlmair et al., 2012) i.e. whether a specific task is an end task or the means to have another task performed. Many task abstraction methods presented in the field of visualization (Amar et al., 2005; Andrienko and Andrienko, 2006; Gotz and Zhou, 2009; Weaver, 2007; Yi et al., 2007) are based on a low-level description of user tasks performed in various contexts. On the other hand, several methods are based on a high-level description (Pirolli and Card, 2005; Liu and Stasko, 2010; Klein et al., 2006; Amar and Stasko, 2004) of user goals. To close this gap, Brehmer and Munzner (2013) presented an interface and domain-independent multi-level task typology where complex tasks are described by analyzing their linkage to simpler ones. Brehmer and Munzner (2013)'s typology is based on reflecting on the three questions in all abstraction levels simultaneously: *why is a task performed*, *how is a task performed* and *what are the task's inputs and outputs*. There are several limitations of the aforementioned task abstraction methods. First, their organization is central to describing the users' behaviour which can make the model dependent to particular users. Second, for an interface developed based on these models, if the user tasks are ill-defined, the interface may work improperly (Marai, 2017). Third, decision-making is not considered as an explicit task (Dimara and Stasko, 2021), while the whole visualization design discipline is centralized to decision-making (Cook and Thomas, 2005; Munzner, 2014; Spence, 2014; Ward et al., 2015)

Unlike the task abstraction techniques proposed in the field of visualization which focus on describing "why and how is a task performed", the WDA technique describes the criteria within which a task *must be performed* such that the high-level system goals are met. The technique was developed as part of the EID framework aiming to help domain experts manage complex tasks of the system they work with. By revealing the means-ends relationships between tasks and constraints underlying a complex problem, WDA supports users in building decision-making strategies according to the system's high-level goals (Naikar, 2013; Burns and Hajdukiewicz, 2017). Since the WDA technique is interface-, context- and also user- independent and supports users in the decision-making tasks, in this thesis, I have applied this technique to derivation of the interface tasks. With such approach the resulting interface is expected to direct (or shape) the users actions (or behaviour) towards the system's operational goals.

2.3 Decision support concepts developed for air traffic controllers

Previous research have followed an EID approach for developing several separation-assistance interface concepts for both pilots and ATCos. Van Dam et al. (2004, 2008) developed a conflict-support interface which enabled pilots to detect approaching conflicts and re-plan a conflict-free trajectory. By analyzing aircraft motion in the horizontal plane, Van Dam et al. (2008) proposed a solution space diagram concept that visualized the links between aircraft speed and heading dynamics to pilots so that they can select a conflicting-free strategy. Building on Van Dam et al. (2008)'s design, Heylen et al. (2008); Ellerbroek et al. (2013) developed a 3D self-separation assistance tool where altitude dynamics were presented as well. Beernink et al. (2015); Bijsterbosch et al. (2016); Lodder et al. (2011); Mercado-Velasco et al. (2010) extended Van Dam et al. (2008)'s design by centralizing the functionality of a separation-assistance tool to ATCos (rather than pilots). Lodder et al. (2011); Beernink et al. (2015) proposed an altitude-extended version of Van Dam et al. (2008)'s design which could support ATCos in visualizing the altitude-based information only within a limited range of neighbouring flight levels. With respect to interaction design aspects, in the designed 3D separation-assistance interfaces mentioned (Lodder et al., 2011; Beernink et al., 2015; Mercado Velasco et al., 2015), the altitude based information was available to ATCos upon their request.

With respect to integration of vertical solutions, several limitations exist in the aforementioned designs. First, the functionality supported by visual encodings in showing the altitude-based solutions were limited to flight levels adjacent to the altitude an aircraft is flying (not all possible solutions were shown). Second, the visual encodings were available to ATCos only upon their request. This makes it difficult for the ATCo to simultaneously compare possible solutions between multiple aircraft. Third, ATCos needed to infer the information regarding ROCD solutions on their own (ROCD solutions were not visualized). In this thesis, I have applied information visualization techniques resulting in the design of VA interfaces, which do not have these limitations.

3

Summary of Contributions

In this section, I summarize the contributions I have had in each publication included in this thesis. The order of the publications depicts how the design process evolved throughout this thesis. For each publication, Table 3.1 specifies the contribution made to the field of visualization, and the details about the evaluation studies performed. Visual encodings for each designed interface as well as more details about the evaluation study parts are described in each corresponding subsection.

Table 3.1: Details of the contributions for each publication included in this thesis

Study	**Interface**	**Contribution**	**Experimentation parts**
1	HTA-Viz	Visual encoding & interaction design Evaluation	1. Quantitative (8 ATCos) 2. Semi-structured interview (8 ATCos)
2	ATL-Viz RAD-Viz	Visual encoding & interaction design Evaluation	1. User study (2 ATCos) 2. Quantitative (14 ATCos)
3	ATL-Viz RAD-Viz	Domain problem characterization Evaluation	Quantitative (14 ATCos and 38 novices)
4	ATLViz-cplx	Visual encoding & interaction design Evaluation	Qualitative (3 ATCos)

3.1 Paper I: the prototype study

Zohrevandi, E., Westin, C.A.L., Lundberg, J. & Ynnerman, A. (2020). *Design of a Real Time Visual Analytics Support Tool for Conflict Detection and Resolution in Air Traffic Control.* In EuroVis (Short Papers, pp. 31-35).
DOI: 10.2312/evs.20201044

This paper presents the visual encoding design of an interactive VA interface called HTA-Viz. HTA-Viz visualizes solutions to CD&R task in real-time by emphasizing the heading, time and altitude information about aircraft that are in conflict. The design study of HTA-Viz includes several activities which are: an initial WDA, iterative rounds of programming, sketching, discussion sessions with a domain expert, a quantitative and, a qualitative evaluation study with eight active ATCos. The HTA-Viz is developed based on formulating and solving aircraft movements in a relative coordinate system.

Figure 3.1 shows the HTA-Viz interface consisting of two displays. As depicted in the figure, on the left display, aircraft position is shown on an x-y plane and heading conflict zones are integrated into aircraft icon in form of colored sections. The right display is called the time-altitude (TA) display. As depicted in Figure 3.1, a polar-graph visualization technique is used to construct the TA display which, shows altitude-based solutions for conflicting aircraft in the temporal domain. A quantitative evaluation study was performed on the HTA-Viz followed by a semi-structured debriefing. The questions asked at the debriefing session can be found in A.1.2. Several ATCos who participated in the debriefing session requested a visual representation showing aircraft ROCD solutions. Therefore, the visual encoding design of the TA display was improved as depicted in Figure 3.2. As can be seen from the figure, a composite-glyph based technique has been applied to integrate both horizontal and vertical solution spaces on the TA display. To avoid clutter, the composite glyph of aircraft flying at adjacent flight levels are shown as small circles. By double clicking anywhere on the screen, ATCos can visualize the solution space glyphs of these aircraft.

My contribution in this paper was the literature review, conceptual design, implementation, and development of the interface, scenario design, data collection, conducting the evaluation study and writing the entire content for the draft of the paper. Analyzing the results was done in collaboration with co-authors. In the submitted version of the paper, the writing was improved through collaboration with the co-authors and their constructive feedback.

3.2 Paper II: the ATL-Viz study

Zohrevandi, E., Westin, C.A.L., Lundberg, J. & Ynnerman, A. (2022, February). *Design and Evaluation Study of Visual Analytics Decision Support Tools in Air Traffic Control.* In Computer Graphics Forum (Vol. 41, No. 1, pp. 230-242). DOI: 10.1111/cgf.14431

This paper contributes in the visual encoding and interaction design, and evaluation of two VA interfaces that promote contextual awareness and support 'what-if' and 'what-else' probes in the spatio-temporal domain. The designed interfaces aim to improve information integration and support ATCos in prioritizing conflict resolution. The interfaces are called angular time line visualization (ATL-Viz) and radial time visualization (RAD-Viz). As the starting point for the design of ATL-Viz, I conducted a user study with two ATCos on the improved version of the HTA-Viz prototype (as shown on Figure 3.2). The material I designed for the user study can be found in

Appendix A.2.1. The outcome of the user study led to the design of ATL-Viz as shown in Figure 3.3.

ATL-Viz consists of two displays. The left display represents a simplified version of the current ATC radar screen. As depicted in the figure, on the radar display aircraft icon group is shown by green circles. Circle diameter represents lateral safety separation criteria (5 nautical miles). The green line shows aircraft heading direction. To avoid clutter, the label next to each aircraft icon group can be dragged using mouse. The information each label contains is as following. In the first row of the label, aircraft callsign followed by aircraft ground speed shown in knots (ground speed is a vector sum of true airspeed and wind velocity[1]. In the second row of the label, aircraft rate of climb is shown in hecto feet/minute with an upward or downward arrow symbol next to it which shows whether the aircraft is climbing or descending, aircraft current flight level is shown followed by its destination flight level. In the last row, aircraft type, weight category and heading angle (in degrees) are shown. The TA display of ATL-Viz, maps the information about time and altitude on a polar graph, only for aircraft that are in a conflict. On polar graph radial axis, circles represent flight levels, increasing outwards. On the angular axis time remaining to conflict is shown in minutes increasing clockwise. The black line directed towards 3 o'clock is separation loss reference line. When an aircraft pair meet on this line, it means that both vertical (1000 feet) and horizontal separation (5 nautical miles) are lost. There is another black line which is directed towards the aircraft pair in conflict and moves with them as time passes. This line is always directed towards the most imminent conflict. The colored curves seen on the TA, represent aircraft vertical profile. The vertical profile of aircraft pair in conflict with each other have the same color. Each aircraft is shown on the TA with a glyph. Upon hovering mouse over an

[1] As mentioned in Section 1.5.2, in all studies conducted throughout this thesis constraints imposed by weather (e.g. wind effects are neglected)

aircraft glyph, the glyph size increases enabling ATCos to see detailed information about solution spaces.

Figure 3.4 describes the information each visual item on the glyph represents. The glyph consists of two co-centric circles. On the outer circle, the green line indicates heading direction ranging from 0 to 360 degrees increasing clockwise. The heading for the shown aircraft sis zero. The red section on top of which the heading line is placed, indicates heading conflict criteria. On some aircraft glyph, one might see brown patterned sections as well. These sections indicate heading conflict criteria for potential conflicts. This means if heading is changed inside the patterned section, the current conflict will be resolved but a new conflict with another aircraft will be created. In brief, the heading solution space is indicated by the white section. On the inner circle, ROCD solution spaces are shown. The inner circle splits by a line which is aligned to the time line that the aircraft icon is located on. The area behind the time line (patterned green section) does not imply any meaning and is used to indicate aircraft selection. The grey area indicates the ROCD range with which the selected aircraft can fly. The black line aligned with the current flight level the aircraft is flying on represents zero rate of climb. The line splits the ROCD range into two sections. The section faced at lower flight levels represents rate of descent range and the line at the edge represents maximum rate of descent. The section faced at higher flight levels represents rate of climb range and the line at the edge represents maximum rate of climb. The colored line inside the grey area shows current rate of climb. The current rate of climb line has the same color as the aircraft vertical profile curve on the TA as well as the glyph outer circle boundary. The colored section inside the grey area represents rate of climb conflict criteria. In brief, the aircraft glyph on the TA shows two solution spaces. The white section inside the outer circle, indicates the heading solution space. The grey section inside the inner circle indicates the ROCD solution space.

The designed glyph is an interactive visual encoding. Right clicking on both circles allows ATCos to explore changes. By right clicking on the outer circle a dashed line appears which allows exploration of heading changes. Right clicking on the inner circle allows exploring different ROCD changes. Upon left clicking on the outer circle a confirmation box appears next to the glyph. For the changes to happen, the selected heading or rate of climb value should be confirmed. To clear an aircraft to a new flight level, the new flight level value should be typed and "clear to FL" button should be pressed. Speed changes can be applied using keyboard buttons.

One important characteristic I considered in the design of ATL-Viz was to improve task prioritization. Relying on the work of Fuchs et al. (2013) which showed positive effects of clock metaphor on monitoring tasks, I mapped the time and altitude information on the polar graph axis in a way that it implies a clock metaphor. To test his effect, I designed RAD-Viz. The main difference between the ATL-Viz and RAD-Viz is how information is organised (i.e. inverted) on the time and altitude axes. In RAD-Viz, time is visualized as circles, with a loss of separation occurring when aircraft in conflict reach the outermost circle. Altitude is in RAD-Viz visualized on angular axis of the polar graph, increasing clockwise. Figure 3.5 depicts how the same traffic scenario visualized on ATL-Viz, is visualized on RAD-Viz.

I conducted a quantitative evaluation study where a comparison between both ATL-Viz and RAD-Viz was made against a simulated version of current ATC display (used as the control condition). 14 ATCos participated in the study. 7 ATCos participated in the comparison study between ATL-Viz and the control display and 7 others participated in the comparison study between RAD-Viz and the control display. Figure 3.6 depicts how the designed traffic scenario (the same traffic as shown on ATL-Viz and RAD-Viz in figures 3.3 and 3.5) was shown on the control condition.

The control condition consisted of two displays i.e. a radar display and a conflict and risk (CARD) display. The radar display was the same among ATL-Viz, RAD-Viz and the control condition. On the CARD display, aircraft pairs in conflict with each other are shown in form of moving labels. On CARD x-axis, time remaining to conflict is shown while on the y-axis, the distance between the aircraft pair at the closest point of approach is shown. ATL-Viz and RAD-Viz in figures 3.3 and 3.5 indicate five conflict pairs exist in the designed scenario, while CARD in Figure 3.6 shows only two conflicts. This is because the time remaining to conflict range shown on the CARD is 12 minutes. To visualize conflicts happening later, CARD time range should be increased manually. The evaluation study consisted of three parts: a training session where ATCos watched a 20-minutes video where the designed visual encodings were explained followed by a familiarization session where they interacted with the tool, a questionnaire study and, a simulation study. The questions I designed for the questionnaire session, can be found in Appendix A.2.2. Because of the restrictions imposed due to COVID-19 pandemic, I programmed and combined all study parts into a standalone executable file. The file was sent out to ATCos and they sent me back the log files which were later analyzed. The aim of the study was to compare the effects of visualization concepts on ATCos engagement in processing solutions suggested by the interfaces. Results showed that the visualizations support ATCos' ability to understand and resolve conflicts. Based on the results, general design guidelines for time-critical domains are proposed.

My contribution in this paper was the literature review, conceptual design, implementation, and development of both the ATL-Viz and the RAD-Viz as well as the control display. I also programmed and integrated the experiment procedure into the designed interfaces so that the study could be conducted entirely remotely and offline. When writing the paper, I wrote most of the content for the draft of the paper.

The introduction section and the first sub-section of the results section was written by co-authors. The training video, the questionnaire study and the scenarios for the experiment was designed by me. The scenarios were improved through collaboration with co-authors. Analyzing the results was done in collaboration with co-authors. In the submitted version of the paper, the writing was improved through collaboration with co-authors and their constructive feedback.

3.3 Paper III: the novice-expert comparison study

Zohrevandi, E., Westin, C.A.L., Vrotsou, K. & Lundberg, J. (2022, June). *Exploring Effects of Ecological Visual Analytics Interfaces on Experts' and Novices' Decision-Making Processes: A Case Study in Air Traffic Control.* In Computer Graphics Forum (Vol. 41, No. 3, pp. 453-464).

DOI: 10.1111/cgf.14554

This study was conducted as a result of the findings I found from the ATL-Viz study (paper II). The aim of this study was to explore possible benefits of ATL-Viz and RAD-Viz to improve novices' understanding of the situations as well as their decision-making process. The same experimental evaluation study conducted in paper II was conducted in this study but this time, with novice users. Since the COVID-19 pandemic restrictions were still in place, the study was conducted remotely. To make sure novices have understood all the visualization concepts, I integrated the training video into a confirmation of understanding questionnaire and logged novices responses to the questionnaire. The log files showed the answer each participant had selected for each question and their time to answer the questions. If a participant selected a wrong answer to a question, the program encouraged them to re-watch a particular part of the training video where the visual encodings relevant to the questions were explained. The log files showed all those participants who had selected a wrong answer had re-watched the concepts and had selected the correct answer after the re-watch. The questions I designed as a confirmation of understanding for novices can be found in Appendix A.3.

The main contribution of this paper is threefold. First, the application of an ecological interface design approach to the development of ATL-Viz and RAD-Viz is described. Second, a human-in-the-loop experiment with forty-five novices was performed within a simplified ATC simulation environment. Third, by performing an expert-novice comparison I investigated the extent to which effects of the proposed interfaces can be attributed to the subjects' expertise. The results show that the proposed ecological VA interfaces improved novices' understanding of the information about conflicts as well as their problem-solving performance. Further, the results show that the beneficial effects of the proposed interfaces were more attributable to the visual representations than the users' expertise.

My contribution was the literature review, conducting the WDA analysis, conducting the evaluation study and writing the entire content for the draft of the paper. Analyzing the results was drafted by me and improved through discussions with co-authors. I also designed and programmed the training session for novices, programmed and integrated the experiment procedure into the designed interfaces so that the study could be conducted entirely remotely during the COVID-19 pandemic. In the submitted version of the paper, the writing was improved through collaboration with co-authors and their constructive feedback.

3.4 Paper IV: the ATLViz-cplx study

Zohrevandi, E., Vrotsou, K., Lundberg, J., Westin, C.A.L. & Ynnerman, A. *Design of a Visual Analytics Decision Support Tool to Manage Traffic Complexity in Real Time: A Case Study in Air Traffic Control.* Work in progress.

The idea of this study formed based on the outcome of my master thesis research project (Zohrevandi et al., 2016) and the ATL-Viz study (paper II). Studies have shown that the complexity caused by the traffic patterns in the airspace drives ATCos workload (Djokic et al., 2010; Delahaye and Puechmorel, 2015; Gomez Comendador et al., 2019). Based on the ATL-Viz study findings, the designed visual encodings improved ATCos understanding of the conflict situations and improved their interaction with the interface. Therefore, I decided to design visual encodings to facilitate detection and resolution of complex traffic patterns in the airspace for ATCos aiming to enable them to decrease their workload. This paper presents novel visual encodings designed for this purpose. The interface supports the users in detecting complex clusters of aircraft and uses visual representations to propose re-routing. Figure 3.7 depicts the designed visual encodings for complex cluster detection on ATLViz-cplx. ATLViz-cplx consists of a radar display (to the left) and the complexity visualization display (to the right), on which, aircraft forming a complex cluster are shown on a circle. The circle radius is drawn proportional to the cluster complexity level and its position correlates to the geometric centre of the aircraft on the radar display. Two spider graphs are shown inside the cluster circle representing each aircraft contribution to the reduction of complexity. The cyan graph shows heading contribution while the red graph shows speed contribution. Upon double clicking anywhere in the cluster, the aircraft belonging to the cluster on the situation display are colored in blue and labels are assigned to them in both views. To further highlight aircraft in conflict within a complex cluster, a box is drawn around their labels. As can be seen aircraft A and B are in conflict in the selected cluster. The cluster visualization display facilitates decision-making for ATCos in two aspects. First, as can be seen from the figure, on the radar display, more aircraft seem to be forming a cluster. But in reality these aircraft are either vertically far or will diverge within the next 2 minutes. Second, using the spider graph visualization, the ATCo can quickly identify the aircraft whose heading or speed should be changed to efficiently reduce the cluster complexity (with minimum number of state changes). The cluster visualization of Figure 3.7 that changing aircraft B's heading will reduce the complexity of the cluster the most.

Upon double clicking on an aircraft of the cluster the complexity glyph is shown as depicted in Figure 3.8. The complexity glyph is an enhanced version of the conflict solutions glyph designed in the ATL-Viz study (see Figure 3.4). Solutions to complexity are shown as two plots. depicting how different re-routing strategies yield reduction of complexity for each individual aircraft. The blue plot shows cluster complexity variations with heading change. The red plot shows complexity variations with speed change within 100 knots change range (± 50 knots from the current speed). The speed plot is enclosed inside a rectangle which is always aligned parallel to the heading direction with current speed marked by a dashed-red arrow. The speed change values are written inside the speed plot box. The values increase in line with the heading direction and decrease opposite to the heading direction. For example, the heading plot visualization shows that increasing the current heading will decrease the complexity. Heading change values can be explored by right clicking inside the outer circle. To apply changes a left click must be made on the outer circle after which a confirmation box appears. On the confirmation box the selected heading value is shown. Upon clicking on the confirm heading button, the changes are applied.

To investigate the concepts' usefulness, I conducted a qualitative study with three fully licensed ATCos, where they worked on a designed traffic scenario once with and once without the support of the visual encodings. The questions I asked ATCos during the session can be found in Appendix A.4. During both conditions ATCos reported the complex patterns they detected, the level of complexity they assigned to each detected pattern and how they approached resolving the complexity of the patterns they detected. The results showed that the interface can enable ATCos detect and resolve traffic patterns faster and more efficiently.

My contribution was the literature review, conceptual design, implementation, and development of the ATLViz-cplx interface, traffic scenario design, conducting the evaluation study and writing the entire content for the draft of the paper. In the submitted version of the paper, the writing was improved through collaboration with co-authors and their constructive feedback.

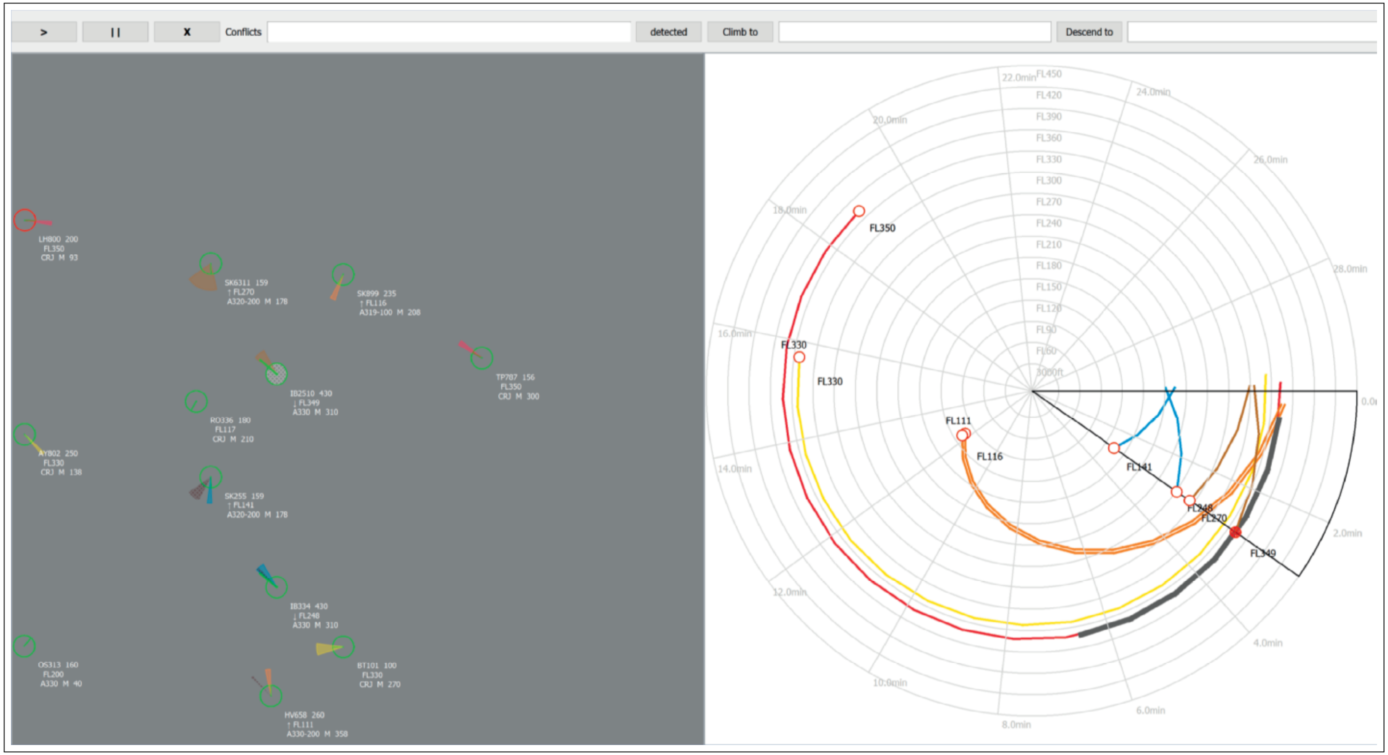

Figure 3.1: HTA-Viz initial prototype consisting of two displays. On the radar display (to the left), the heading conflict zones are integrated to the aircraft icon. The colored sections represent heading conflict zones. The TA display (to the right) shows vertical profile of aircraft in conflict as well as urgency of the conflict.

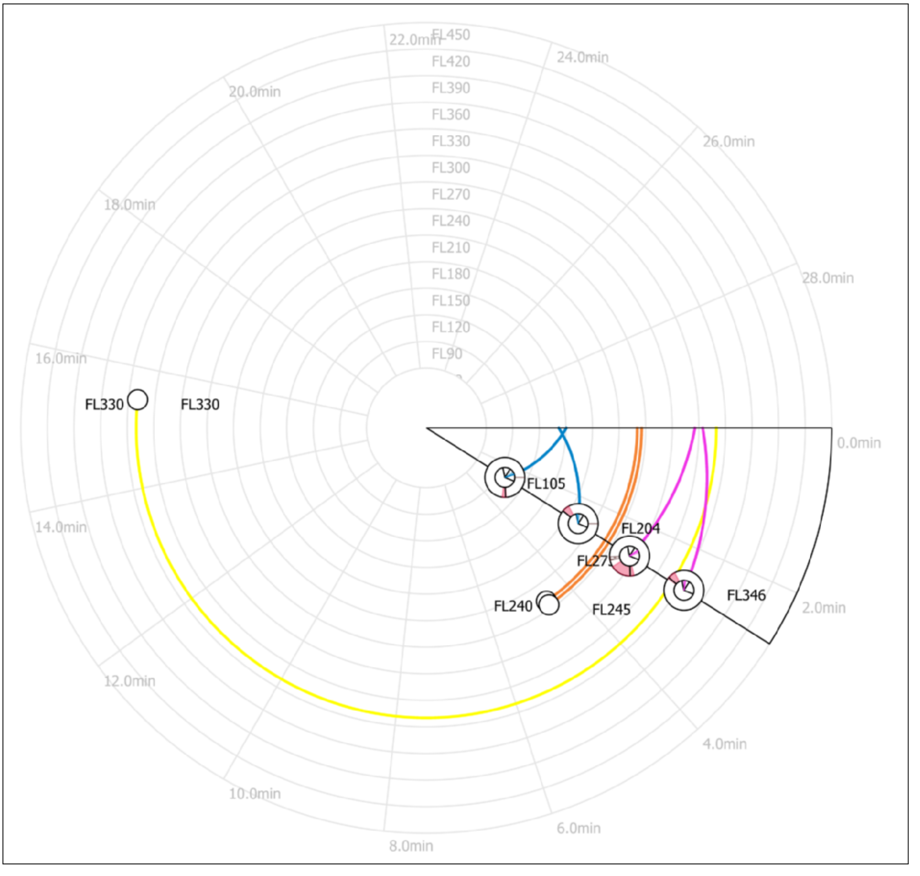

Figure 3.2: Improved visual encoding design of the TA display on the HTA-Viz interface. Based on the outcome of the qualitative study conducted with ATCos both horizontal and vertical solutions to conflict were integrated into a composite glyph. To visualize the detailed information about solution spaces, ATCos needed to manually zoom in on an aircraft glyph.

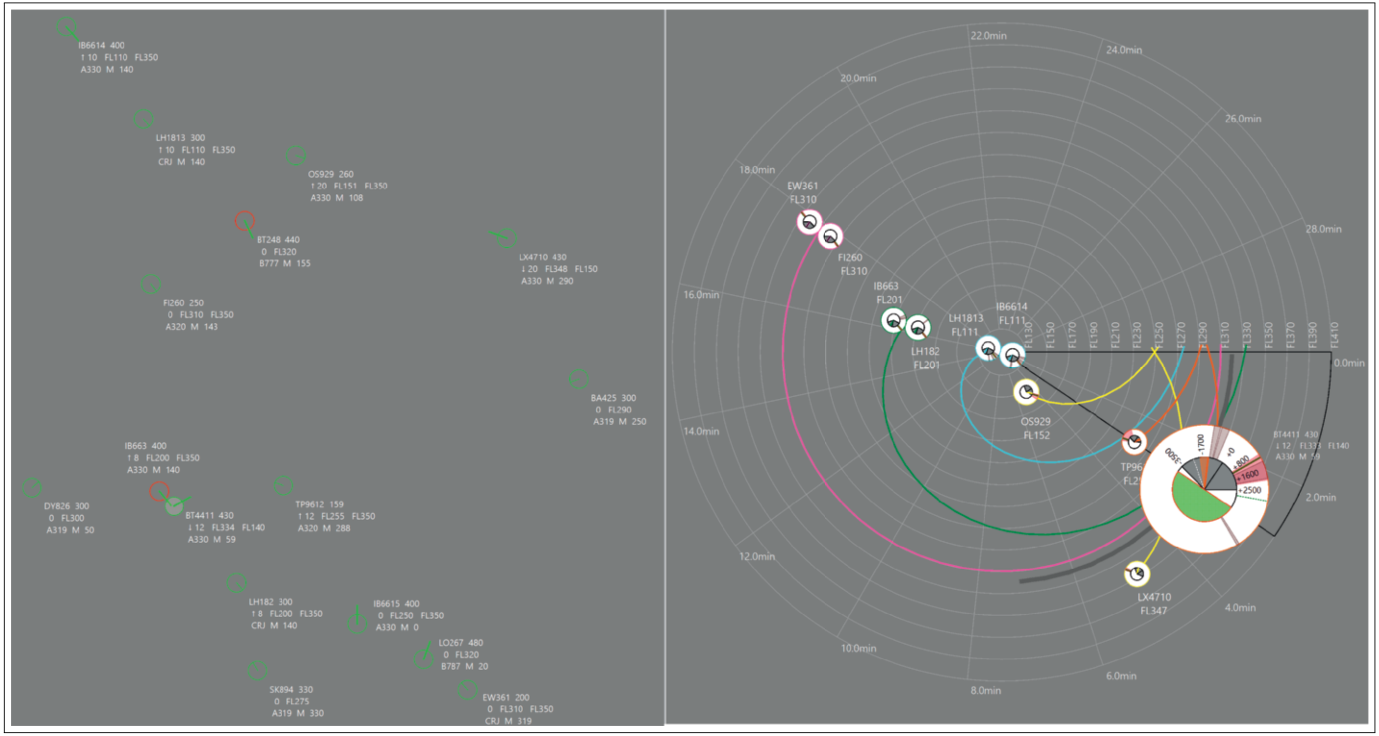

Figure 3.3: The designed traffic scenario as shown on the ATL-Viz. By hovering the mouse over the aircraft glyph on the TA display, the size of the glyph increases enabling ATCos to visualize and compare in real-time the detailed information about both horizontal and vertical solution spaces.

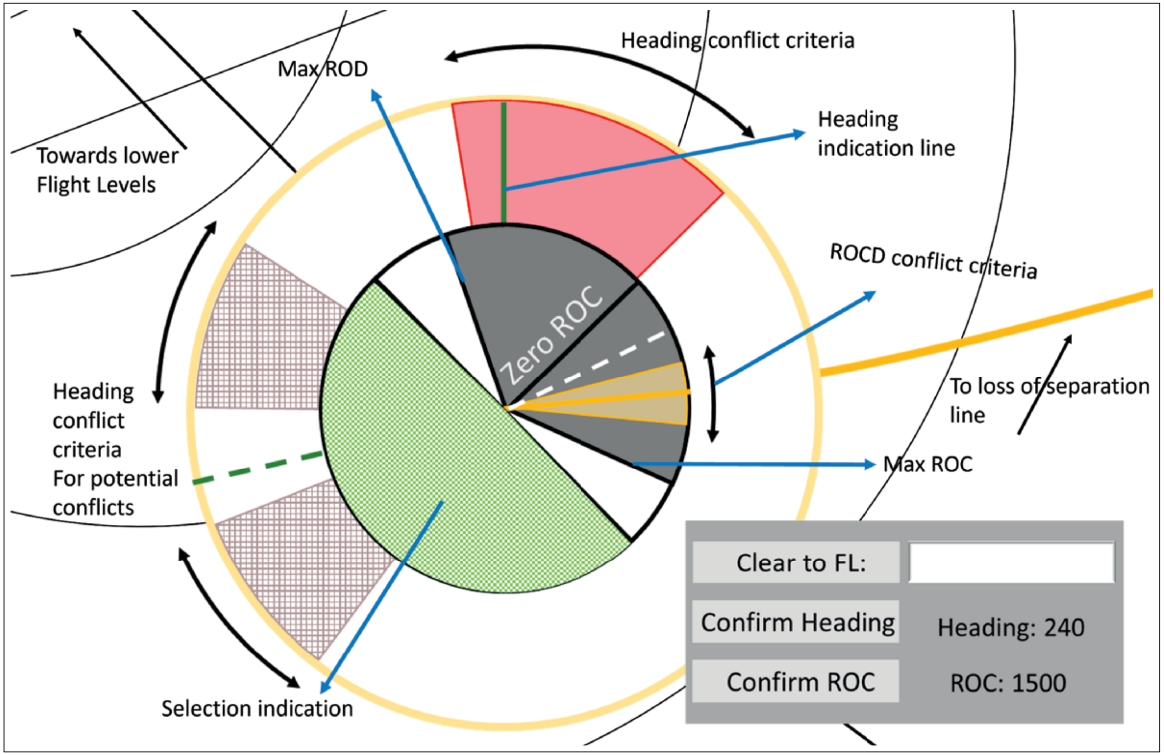

Figure 3.4: Visual items of the composite glyph show detailed information about horizontal and vertical solution spaces for aircraft in a conflict. The white and green dashed lines allows ATCos to explore ROCD and heading changes respectively.

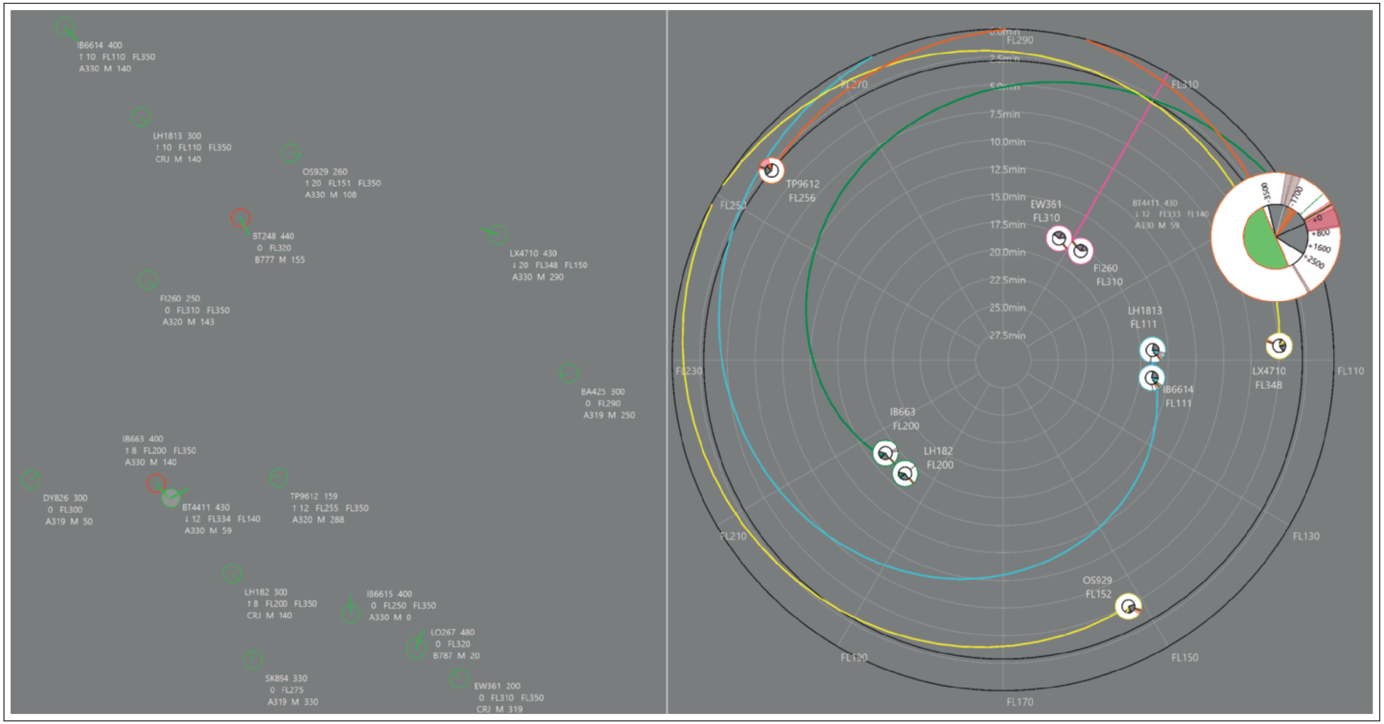

Figure 3.5: The designed traffic scenario as shown on the RAD-Viz. RAD-Viz shows the same information as ATL-Viz. However, on RAD-Viz time and altitude information are mapped on inverted axes of the polar graph.

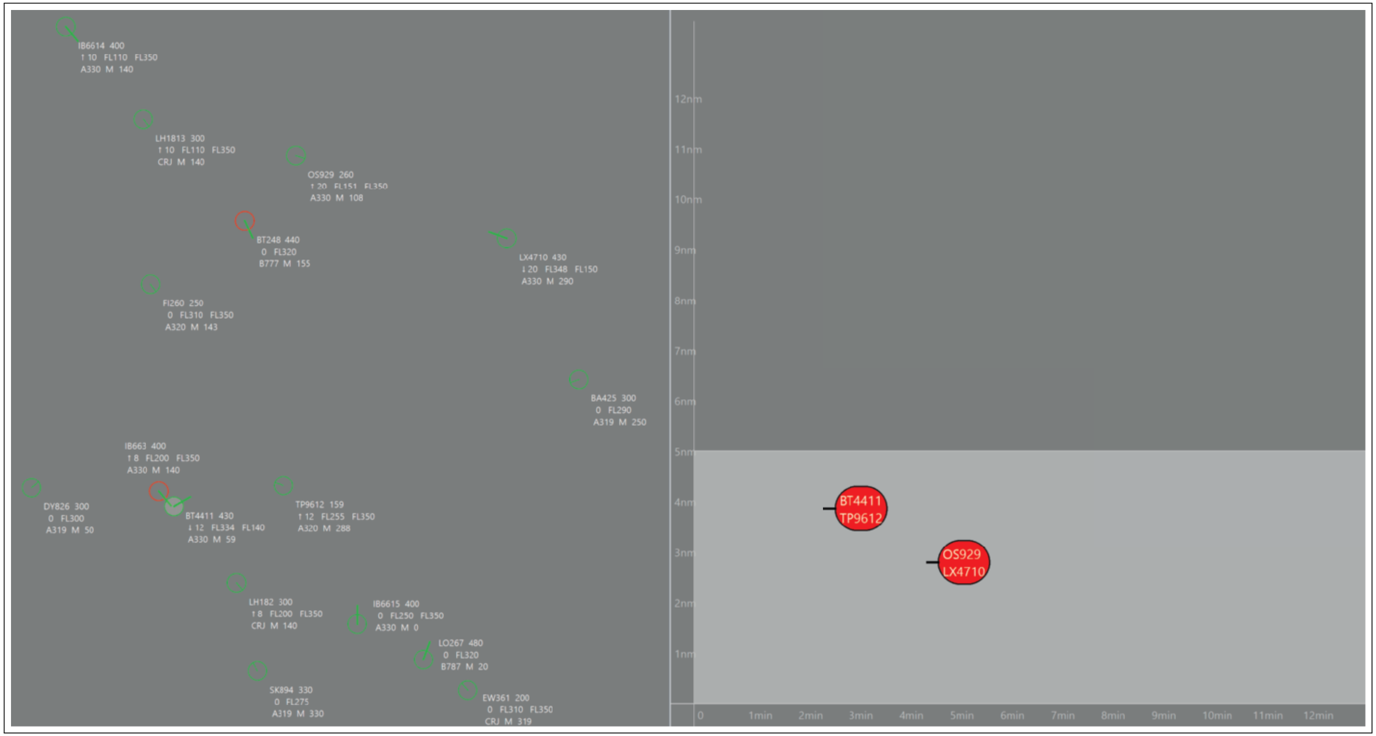

Figure 3.6: A simulated version of the current ATC displays used as the control condition for both the ATL-Viz study and the novice-expert comparison study.

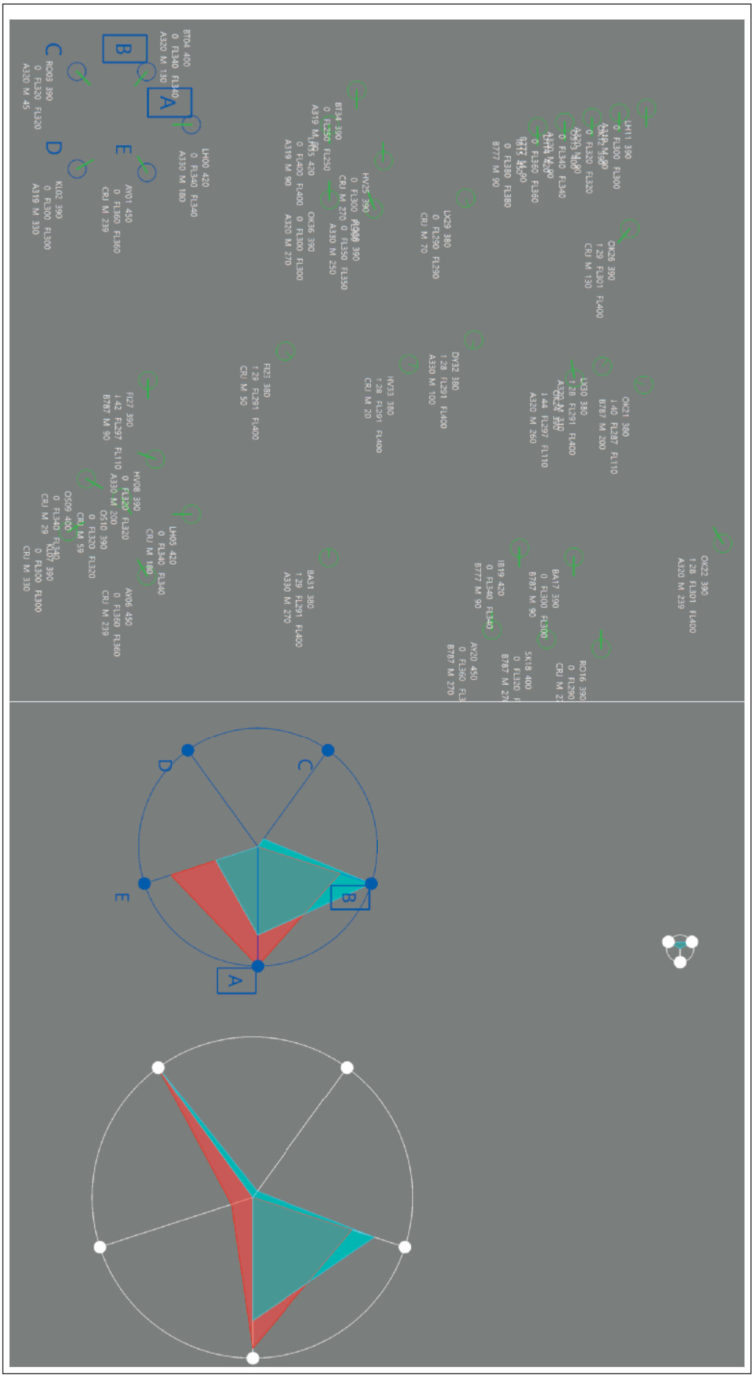

Figure 3.7: Visual encodings design of ATLViz-cplx interface. The designed concepts support ATCos in detecting complex clusters in the traffic.

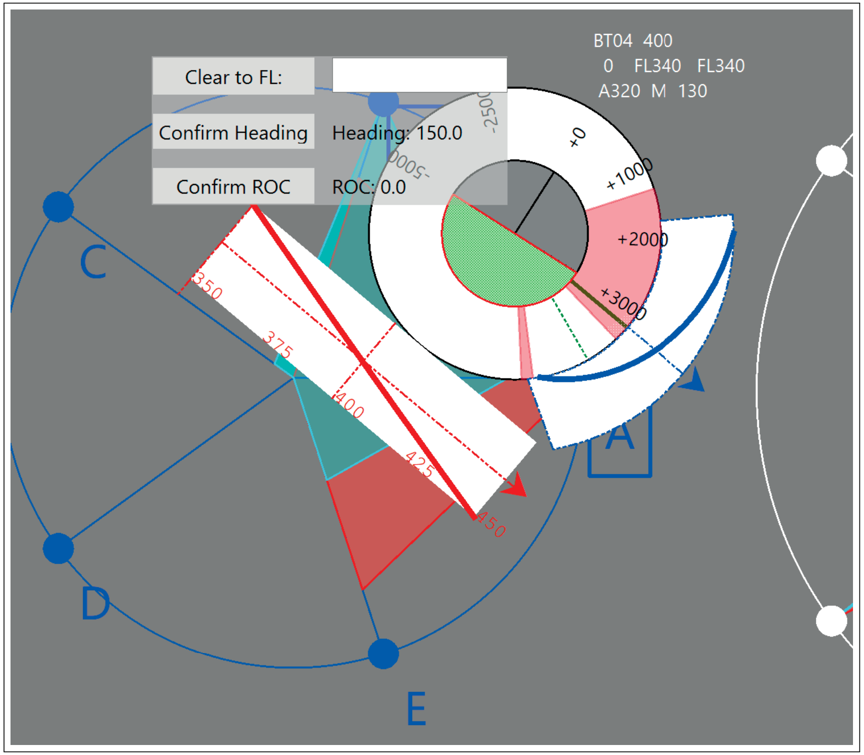

Figure 3.8: On ATLViz-cplx, complexity plots were integrated to ATL-Viz conflict glyph. For a selected aircraft, the complexity plots show how speed and heading changes affect complexity of the cluster. Integration of complexity concepts to the conflict glyph, enables ATCos to consider reducing traffic complexity while resolving conflicts.

4

Conclusion

The principal aim of this thesis was to design visual representations to facilitate decision-making for operators of safety-critical domains. ATC as an example of a safety-critical domain was the focus of my thesis and two core tasks of the ATC domain were studied; CD&R, and, traffic complexity management. I studied these two complex tasks and designed visual representations to facilitate decision-making for ATCos. Thereto, this thesis contributed to the knowledge of interface design for safety-critical domains in four aspects i.e. (a) Visualizing task complexities, enhancing ATCos performance and efficiency during CD&R task by (b) focus+context visualization of resolution strategies and (c) metaphoric visualization of time, and, (d) supporting ATCos in reducing traffic complexities by visualizing the complex traffic patterns and solutions to them.

The novelty of this thesis lies within how I contributed to each of these aspects. First, to obtain "what information needs to be visualized", I studied the underlying complexity within ATC CD&R, and complexity management tasks. Second, to improve ATCos' performance, a composite glyph was designed to facilitate what-if and what-else probe on the resolution strategies. To enhance their efficiency, task prioritization (resolving conflicts based on their urgency) was improved. Third, to support ATCos in reducing emergence of future complex patterns, traffic complexity and aircraft state changes effects on the traffic complexity were visualized. In the following sections, I will explain how in each research study I conducted, I attempted to reach the principal aim mentioned above and how the outcome of my research contributed knowledge to the field of visualization design.

4.1 Interface design based on visualization of the underlying complexity within tasks

Unlike previous works in the field of visualization where the interface design heavily relies on what the operator does (see Section 2.2), in this thesis, the foundations for derivation of the tasks that must be supported by the interface are shaped through analyzing the working environment of the operator rather than the operators themselves. As presented in the novice-expert comparison study (Paper III), the information that needs to be visualized by the interface was derived from analyzing the CD&R task of an ATCo in four hierarchical levels.

At the first level, I derived the overarching goals of the ATC domain i.e. maintaining safety, enhancing ATCos efficiency and performance. At the second level, I studied the criteria used by ATC researchers to evaluate how well the overarching goals of ATC are met. By analyzing these criteria, I defined measures that can be used to evaluate how well goals for the core task of CD&R are fulfilled. These measure were: spatial separation, supporting ATCos during high workload situations, visualizing consequences of their decisions and supporting them in task prioritization. For each of the defined criteria, research questions were proposed and to obtain answers for each question, separate state-of-the-art studies were conducted. Based on this analysis, I determined the functions that a decision-support system for CD&R must support in order to fulfill the measures defined in the second step. These functions were: identifying conflict criteria, identifying vertical separation criteria, identifying potential conflicts criteria and supporting ATCos temporal awareness. At the fourth level, based on the system functions obtained from the third level, specific functionalities that must be afforded by individual interface objects were derived. These functionalities were: detecting, and, analyzing solutions to conflicts, visualizing heading solutions, visualizing ROCD solutions, visualizing flight level changes, visualizing solutions to potential conflicts and visualizing time remaining to conflict.

Through hierarchical analysis of the CD&R task, the complexity of the tasks were broken down from overarching goals to individual interface functionalities. Assigning each function to a visual item enables the user to visualize the relationship between visual items of the interface and understand the links between functions. As presented in the ATL-Viz study (paper II), two VA interfaces were designed based on the described design approach, both supporting the same functionalities.

Through experimental evaluations with experts in the ATL-Viz study and novices in the novice-expert comparison study, I found that the two designed interfaces improved users understanding of conflicts and how to solve them. Based on these findings, I conclude:

- Visualization of the underlying constraints and relationships within ATC CD&R task improves users understanding of the conflict situations regardless of their expertise.

4.2 Composite glyph design for focus+context visualization of various resolution strategies

Prior to this thesis, the visual representations proposed by ATC researchers (see Section 2.3) mainly focused on the derivation of the information to be visualized. Their approach solely relied on the ecological interface design aspects and precise modelling of aircraft motion dynamics. In this thesis, in addition to deriving the information to be visualized (e.g. visualizing altitude-based information to support ATCos during high workload situations), effective ways of communicating such information to the operators was also investigated. Thereto, I applied visualization-based reasoning to identify the appropriate "form" of visual items on the interface. As presented in the novice-expert comparison study (paper III), the outcome of the WDA I performed on the CD&R task revealed the need for visualization of seven sets of information about various resolution strategies. Showing this information to an ATCo was challenging because displaying information additional to what is currently shown on ATC displays, may (a) impede visual search and (b) increase clutter. This can lead to incorrect information encoding and an increased workload for ATCos. In an attempt to design a visual encoding that can convey the information correctly, as presented in the ATL-Viz study, I proposed an interactive composite-based glyph design. To test whether the information visualized on the designed glyph can be encoded effectively, I designed a questionnaire study containing elementary and synoptic tasks. To test whether ATCos expertise affects their effectiveness in understanding the information on the glyph, I replicated and performed the same questionnaire study with novices (paper III). The findings from the studies with both ATCos and novices showed that the designed glyph conveyed the information correctly as the participants answered the questions regarding the information shown on the glyph correctly. To investigate the extent to which the designed glyph affects users' effectiveness in understanding the information, the same questions were repeated in the questionnaire study on a simulated version of the currently used display. The findings of the questionnaire study showed that ATCos understood the elementary and synoptic information on the designed glyph more effectively than on the alternative option. For novices, their effectiveness in understanding the information was improved only for synoptic tasks. For the elementary tasks, novices understood the information on ATL-Viz as accurately as on the control display but their time to understand the information was slower on ATL-Viz than the control display. Based on these findings I conclude:

- Visualization and integration of the information about various resolution strategies (heading change, ROCD change, etc.) to conflicts resolution task in the designed composite glyph, improves users' effectiveness in probing what-if and what-else functionalities regardless of their expertise.
- Users time to understand the elementary information on the designed glyph improved with expertise. This could be because the glyph contained the information that required ATC expertise. Novices might naturally find this information difficult to understand.

To test whether the designed glyph and interactive features affect users' decision-making process during CD&R task, I designed a real-time simulation study where the users' task was to detect and resolve conflicts in real-time. Similar to the questionnaire study, the design was compared with a simulated version of the currently used radar and CARD displays and the study was conducted for both expert and novice users. Findings indicated that the designed glyph was more useful for both expert and novices in terms of mouse hover duration over the glyph and their preference to apply their strategies on the glyph rather than the currently used displays. Therefore, I conclude:

- Real-time visualization and integration of various resolution strategies to conflicts resolution tasks in the designed composite glyph of this thesis is useful for the users and improves their interaction with the interface in the decision-making process regardless of their expertise.

The findings further indicated that while the designed glyph did not affect ATCos' decision-making duration, number of conflicts ignored and time to finish CD&R task, it did improve for novices. Therefore, I conclude:

- The extent to which the designed glyph can improve users effectiveness in the decision-making regarding CD&R task depends on their expertise level. The less expert a user is, the more beneficial the interface is in improving their accuracy in detecting the conflicts and their time to resolve conflicts.

4.3 Metaphoric visualization of time

In an attempt to improve ATCos' task prioritization aiming to improve their efficiency in CD&R, I applied a metaphoric visualization technique to visualize the temporal aspects of the data. As presented in the ATL-Viz study (paper II), the time and altitude information are mapped on a polar graph in a way that it implies the clock metaphor. To test whether such technique affects ATCos' task prioritization, I designed RAD-Viz and compared it with ATL-Viz. While RAD-Viz visualized the same information as ATL-Viz, metaphoric visualization of time remained particular to ATL-Viz. I also compared both ATL-Viz and RAD-Viz with the simulated version of the currently used ATC displays. The findings of the simulation study indicate that ATL-Viz encourages both ATCos and novices to resolve conflicts based on how urgent the situation is. When comparing RAD-Viz with the simulated version of currently used displays, the findings indicated that RAD-Viz, on the contrary to currently used displays, discouraged both expert and novices to resolve conflicts based on how urgent the situation was. Based on these findings, I conclude:

- Metaphoric visualization of time as presented on ATL-Viz improved users' CD&R task prioritization regardless of their expertise.

4.4 Visualization of complex traffic patterns

Even though CD&R is the core task of an ATCo, the complexity of the traffic also drives ATCos' workload. Reducing the complexity of the traffic enables ATCos to reduce the workload they may experience in near future. To support ATCos in managing their own workload, I designed visual representations (as presented in the ATLViz-cplx study) which supports them in reducing the complexity of the traffic situation further. The designed representations featured two hierarchical visual representations. (a) A cluster visualization and (b) a composite glyph. On the cluster visualization, complex clusters in the traffic and their complexity level were visualized in real-time. The aircraft in conflict within each complex cluster were also shown. I applied a spider graph visualization technique for real-time comparison of each aircraft contribution to the complexity of the cluster and how the complexity can be managed. On the composite glyph visualization, the effects of aircraft state changes on the complexity of the cluster were visualized for each individual aircraft. Since the principal aim of this design was to facilitate real-time understanding of complex traffic patterns for the tactical ATCo, these visual representations were integrated to the ATL-Viz leading to the ATLViz-cplx VA interface. To test whether the complexity visualization concepts of ATLViz-cplx supported ATCos in detecting and managing the complexity of the traffic, a qualitative user study was conducted with three ATCos. ATCos worked with the same traffic scenario, once with and once without the support of the complexity visualization concepts. To test the extent to which ATLViz-cplx can support ATCos, five different clusters with varying level of traffic complexity were designed. The ATCos' task was to detect the patterns, sort them based on their complexity level and decide on how to manage the complexity of a particular cluster. The study findings indicated that without the visualization support, some ATCos considered non-complex patterns as complex mainly because of aircraft horizontal proximity. Furthermore, the order of complexity assigned to detected clusters were different from one ATCo to the other. However, with the visualization support they all confirmed the algorithm's detected clusters were complex and agreed with the order of complexity represented by the tool. Based on such findings, I conclude that:

- Visualization of complex traffic patterns and their complexity level **can improve** ATCos' understanding of the traffic complexity.

The study findings also indicated that ATCos could react faster and resolve complex patterns more efficiently with the visualization support as compared to the control condition. Based on such finding, I conclude:

- Visualization of the effects of aircraft state change on the complexity of the traffic patterns, **can support** ATCos in managing traffic complexity.

This can reduce the emergence of complex traffic patterns and potential conflicts, potentially reducing ATCos' workload compared to a condition when visualization support is not provided. However, whether and the extent to which, the designed visual encodings would reduce ATCos' workload remains a question for future research.

5

Discussion and Future Work

In this chapter, I revisit the research goals and challenges raised in the introduction section reflecting on the critical aspects of the methodology I applied and the visual encodings I designed throughout this research work. I further discuss the limitations of the conducted research and devise recommendations for future research. First, the ATL-Viz design is discussed with respect to the WDA methodology I used for mapping the data and my approach to find the "form" of the interface. Second, the critical aspects of the ATLViz-cplx design study are discussed. Finally, limitations for the evaluation studies conducted in this thesis are discussed.

5.1 ATL-Viz design for CD&R

Since visualization task taxonomies are highly dependent on the users' tasks (Marai, 2017; Dimara and Stasko, 2021), it is questionable whether the VA interfaces designed based on these taxonomies can improve decision-making activities. Unlike previously designed VA interfaces which typically lack focusing on decision tasks (Dimara and Stasko, 2021), the WDA technique I used in this thesis focused on supporting operators' in the decision-making. The technique provided a step-by-step guidance to the derivation of interface functions and data mapping I performed in the design of ATL-Viz. In this section I discuss the key aspects as well as the limitations of ATL-Viz with respect to the interface functions and the visual encoding design.

5.1.1 Interface functions and data mapping

ATC tasks are not limited to CD&R, they include changing aircraft speed for controlled time of arrival procedure, giving direct route to an aircraft towards specified way points to have them follow their predefined flight plan or to avoid weather phenomena. ATC tasks in reality incorporate efficiency goals, in addition to safety, and are more complex than what is presented in this thesis. Several research studies prior to my thesis have performed WDA on the ATC tasks. However, the WDA I performed in this thesis is different from the previous WDAs in two main aspects. First, previous WDAs mostly focused on studying all ATC tasks. Therefore, they lack a detailed investigation of the functional requirements an interface must be able to support to facilitate CD&R task in particular. Second, in previous works WDA is performed with the aim of analyzing ATC "work as done" (which is the traditional use for the systems that already exist). In other words, previous works aimed at deriving the functionalities that were missing in currently used systems. In this thesis however, the main goal behind the WDA was to investigate the work domain "as imagined" i.e. what functions should be supported by the interface to improve ATCos decision-making process. Since the focus of my analysis was restricted to CD&R task, the resulting VA interface (ATL-Viz) can be used as a decision support tool for CD&R task only. Therefore, one should not look at ATL-Viz as a VA interface that is oversimplifying the ATC tasks by just aiming to avoid conflicts. ATL-Viz should rather be viewed as a starting point for development of an interface which covers a broader range of ATC tasks. This is a research direction I consider taking for the future.

Even though ATL-Viz enables the user to apply speed changes on an aircraft, it does not visualize the conflict zones for speed change. Knowing that speed change, is a viable solution to CD&R task, a question may be raised concerning why speed change solution space is not visualized by the ATL-Viz. This is because the WDA I performed on the CD&R task, did not reveal a parameter that directly leads to visualization of speed change solutions. In the study conducted by Kirwan and Flynn (2002), ATCos rarely used speed change as a resolution mechanism as it lacked effectiveness in short-term conflict resolution. This is because when cruising at high altitudes, aircraft have small speed envelope (e.g. 10-20 knots) and therefore can not change much. However, since the WDA I performed heavily relied on an extensive literature future studies may reveal ATCos preferences to use speed for resolving specific conflict situations. Therefore, another future direction for my work is to study the applicability of integrating a visual encoding for speed solution space into the designed composite glyph and evaluating the extent to which such visual encoding can enhance ATCos CD&R task.

While the aim of performing the WDA on CD&R task was to facilitate ATCos' decision-making and decrease their workload, a potential problem is that the added information could require more attention and can increase workload especially with dedication of a whole display to the time-altitude visualization on the ATL-Viz. This separate display requires the ATCo to look at two different displays (radar screen and ATL- Viz) and then the glyphs of each aircraft on the ATL-Viz. However, the outcome of the ATL-Viz study indicated otherwise. The study findings showed that the visual representations designed, if integrated to a real ATC simulator, could potentially improve ATCos workload. This is because no significant effect of the designed concepts was found on ATCos workload. This finding refers to a comparison between two displays, a control display with which ATCos have been working for many years and the novel ATL-Viz with which, ATCos have become familiar during a very brief training session (watching a 20-minutes tutorial video). Therefore, although workload was not measured directly, I speculate a potential reduction in ATCos' workload when longer training sessions with ATL-Viz are provided. My speculation lies within the fact that even though the what-if and what-else probe functionalities presented in ATL-Viz are additional information to the currently used ATC displays, previous research shows that ATCos weigh in their options and probe what-if and what-else functionalities in their mind when making a decision on the currently used displays (Xiaotian and Zhang, 2017). Thus, it would be interesting to study in the future the effects of ATL-Viz on ATCos workload when longer training sessions are provided.

5.1.2 Visual form

The ATL-Viz way of mapping the temporal data on a polar graph has been mainly driven by my approach to enhance operators' efficiency in task prioritization. My approach was to imply a clock metaphor. While, Fuchs et al. (2013) argue for the positive effects of clock metaphor and mapping temporal data on a radial chart on monitoring tasks, most of previous works argue against such benefits (Blascheck et al., 2018; Burch and Weiskopf, 2014; Cleveland and McGill, 1984; Goldberg and Helfman, 2011; Heer and Bostock, 2010; Simkin and Hastie, 1987; Waldner et al., 2020). The conclusion made from this thesis however, is that the clock metaphor supports prioritization of which conflict to resolve first, not only for ATCos but also for novices with no prior knowledge in ATC. The reason for the contrast between my results versus previous works could be due to the fact that my design is particular to the context of a safety- and time-critical domain i.e. CD&R in ATC. In the studies which argue against the benefits of clock metaphor, the visualizations used showed static and generic data in the contexts of daily patterns, social networking, statistics and smartwatch display. In a safety- and time-critical domain the situations are more complex with fast dynamics and that could be one underlying reason for why the metaphoric visualization of time benefited the users of this study. To further explore the extent to which the clock metaphor affects users task prioritization, time and data could be mapped on the ATL-Viz linearly. Therefore, another future research direction is to develop an enhanced CARD where time and altitude-based information could be mapped on the x and y axis of a rectangular graph (instead of the polar graph). The designed glyphs could also be implemented. In addition to evaluating the effects of linear mapping of the temporal data, it is worth to investigate whether ATCos familiarity with the CARD display could enhance their performance and efficiency further.

Despite benefits of the ATL-Viz way of emphasizing the vertical separation between aircraft in a conflict, a possible disadvantage could be that it may diminish the horizontal proximity between two aircraft pair. This information is however represented inside my designed composite glyph in form of an emergent feature. Figure 5.1, shows how conflict progression on the horizontal plane can be estimated by the heading conflict zone on the outer circle of the glyph. As can be seen from the figure, the size of HSS visualization indicates the severity of conflict progression on the horizontal plane. The bigger the size of HSS is, the more difficult it will be for the ATCo to resolve the conflict by changing the course of an aircraft.

Knowing the fact that the ATL-Viz way of visualizing the information is fundamentally different from the traditional ATC display and also the fact that ATL-Viz improves users understanding of conflicting situations regardless of their expertise, ATL-Viz could be seen as an interface which reflects an aspect of ATCos mental model that was not reflected by previous studies. This, opens up the possibility for extending the work to a more generic visualization, which could support operators' decision-making in other safety-critical domains. Emergency response management is an example of high-stake safety-critical environment where, highly dynamic and uncertain incidents caused by natural disasters require from the incident operator to analyze large amounts of information and coordinate multiple rescue responders. The fact that time-to-rescue determines the mortality rate, puts the incident operator under a lot of pressure. Therefore, emergency response systems are required to amplify operators' decision-making to enable them to cope with constantly changing circumstances and time pressure. ATL-Viz is primarily highlighting urgency of the situations (time) and altitude-based information. Urgency of the situations is fundamental to all safety-critical domains. The way temporal information is organized on ATL-Viz implies clock metaphor which based on the results of my studies benefits task prioritization. Task prioritization also matters to operators of safety-critical domains (e.g. emergency response). These aspects make the ATL-Viz concept a good candidate for generalization to other domains. Furthermore, the ATL-Viz study findings showed that highlighting ATCos most preferred resolution strategy during high workload situations i.e. altitude-based information (Rantanen and Nunes, 2005; Fothergill and Neal, 2008; Malakis et al., 2010), improved ATCos effectiveness in understanding an aspect of the traffic situation (vertical spatial understanding) which was hidden to them. Replacing altitude-based information with the information that matters the most to the operators of other safety-critical domains, can be the first step for generalization of ATL-Viz to other domains.

5.2 ATL-Viz enhancements for traffic complexity management

During the semi-structured interviews I conducted in the ATLViz-cplx study, when ATCos were asked "how they would detect complex traffic patterns", they all stated that they would use horizontal proximity of aircraft as a measure to investigate the complexity of the cluster. This could be due the fact that horizontal proximity is clearly visualized on the currently used displays, thus making it a parameter for ATCos to investigate complex patterns. Since horizontal proximity is not explicitly visualized on the ATLViz-cplx, it is worth investigating whether ATLViz-cplx could change ATCos way of detecting complex traffic patterns, when used for a longer period.

On ATLViz-cplx, complex clusters are detected in real-time based on the traffic dynamical changes within a 2-minute range. If the shape of the clusters change a lot after a 2-minute update, ATCos may become confused or distracted. The 2-minute time range I selected for the cluster detection algorithm update, was based on the fact that ATCos make decisions by predicting how the traffic will appear in the next 2-minute. The fact that the traffic appearing on their screen may change after 2 minutes is the reason for why they continuously monitor the traffic and revisit their decisions. However, to reduce ATCos monitoring effect a possible future direction my work could have is to design visual encodings which show how the complexity of the cluster will change over a longer period of time.

5.3 Experimentation and evaluation

While the ultimate goal of VA interfaces is to support decision-making tasks (Cook and Thomas, 2005; Munzner, 2014; Spence, 2014; Ward et al., 2015), a considerable number of visualization designs lack investigation of their capability with respect to decision-making support (Dimara and Stasko, 2021). However, the evaluation studies I conducted throughout this thesis, solely aimed at investigating the ATL-Viz capability in supporting ATCos decision-making processes. In this section, I explain four challenging aspects of the evaluation studies I conducted in this thesis.

One limitation of the ATL-Viz study lies within the technical aspects with respect to creating a high fidelity ATC simulation environment. For example, ATL-Viz does not show the information about flight plan, destination waypoint, sector size, it does not consider pilot intention in its simulation environment and aircraft performance characteristics. Even though creating a high fidelity simulation environment was out of the scope of this thesis work (as mentioned in Section 1.5), I do acknowledge that visualizing the flight plan information affects ATCos' way of problem-solving as well as their time to accomplish CD&R task. For example, for two aircraft in a conflict where both are climbing towards the same flight level, depending on whether that flight level is their top of descent or not, an ATCo's decision with regards to which resolution strategy to apply on which aircraft may change. This however does not affect neither the correctness of the studies I conducted in this thesis nor the validity of the results. That is because the same simplification had been made on all display conditions, including the display condition that represents the currently used displays.

Incorporating more realistic assumptions on the rate at which a pilot can turn an aircraft or climb to a cleared flight level makes ATL-Viz a good candidate to be used as an extra display in industrial research settings where more realistic traffic scenarios on real simulators are setup. Thereto, I aim to incorporate aircraft performance characteristics in the design of the solver for the conflict detection algorithm presented in the prototype study (paper I).

In both ATL-Viz and novice-expert comparison studies (papers II and III), the main factor I considered in designing the traffic scenarios was the geometry of conflicts. A variety of conflicts geometries were considered so that strategies acquired by the ATCos in the experiments do not become biased towards a particular resolution type (heading change, altitude change or speed change). This was based on the fact that in the guidelines used for ATCos training programs, resolution strategies are advised based on the conflicts' geometry (Great Britain et al., 2009). However, other factors such as the flow of the traffic in the sector could also affect ATCos' resolution strategies (e.g. the amount of the change they apply, to which aircraft in the conflict they apply the changes, whether they change the state of the neighbouring aircraft that may impose a potential risk of deviation from safety criteria, etc.). One limitation of the traffic scenarios I designed for the studies, was that no attempt was made to make the traffic flow patterns realistic compared to what ATCos view in their every day work. While this may affect the realism of the experimentation, the advantage is that it enabled me to assume that all ATCos who participated in my studies had the same familiarity level with the traffic scenarios. Based on this assumption, we invited ATCos from other countries to participate in the studies. This led to having more participants which increased the validity of the results.

The outcome of the novice-expert comparison study revealed the ATL-Viz capability in shaping novices behaviour, Thus, another future direction of my work could be helping novices learn ATCos problem-solving strategies by adjusting suggestions of the interfaces depending on the ATCos' behaviour and thus expertise level. It is also worth investigating the extent to which novices skills and knowledge are improved when the interface support is removed.

The fact that the ATLViz-cplx study was conducted with three ATCos only, could indicate non-generalizability of the results. To further investigate this, I aim to conduct a more extensive evaluation study with more ATCos in the future.

The restrictions imposed, due to COVID-19 pandemic had adverse effects on the studies conducted as part of this thesis, in particular data collections. Several simulations were only possible to conduct remotely. I dedicated months worth of hard work to integrate the familiarization session, the questionnaire part, and the simulation part. I curated all the aforementioned components into a stand-alone executable program which could run on any computer offline. The size of the program, including all the media content, was only ~ 300 MB, which made it possible to be easily distributed over the internet to all ATCos located in different countries, without the need to install any other software. A major challenge in this process was to work around factors that could interrupt the flow of experiment, e.g. having a study part skipped, moving to the next scenario without having the CD&R task completed, and incomplete familiarization with the interface's interactive features. To alleviate the risk of such interruptions, I added mechanisms in the tool that would warn the user about such interruptions and possible corruption of the log data. Conducting the study remotely/offline also made the use of eye tracking impractical, a technique that otherwise could have given additional insight into the use of the VA interfaces in novices and ATCos decision-making processes. Among the upside, was the fact that we could reach a larger number of ATCos from different countries and novices from various backgrounds, and that they could complete the evaluation study in the comfort of their home. Having both studies (ATL-Viz and novice-expert comparison) conducted successfully remotely, opens up the possibility for conducting more offline studies to investigate further the research directions I devised in this section.

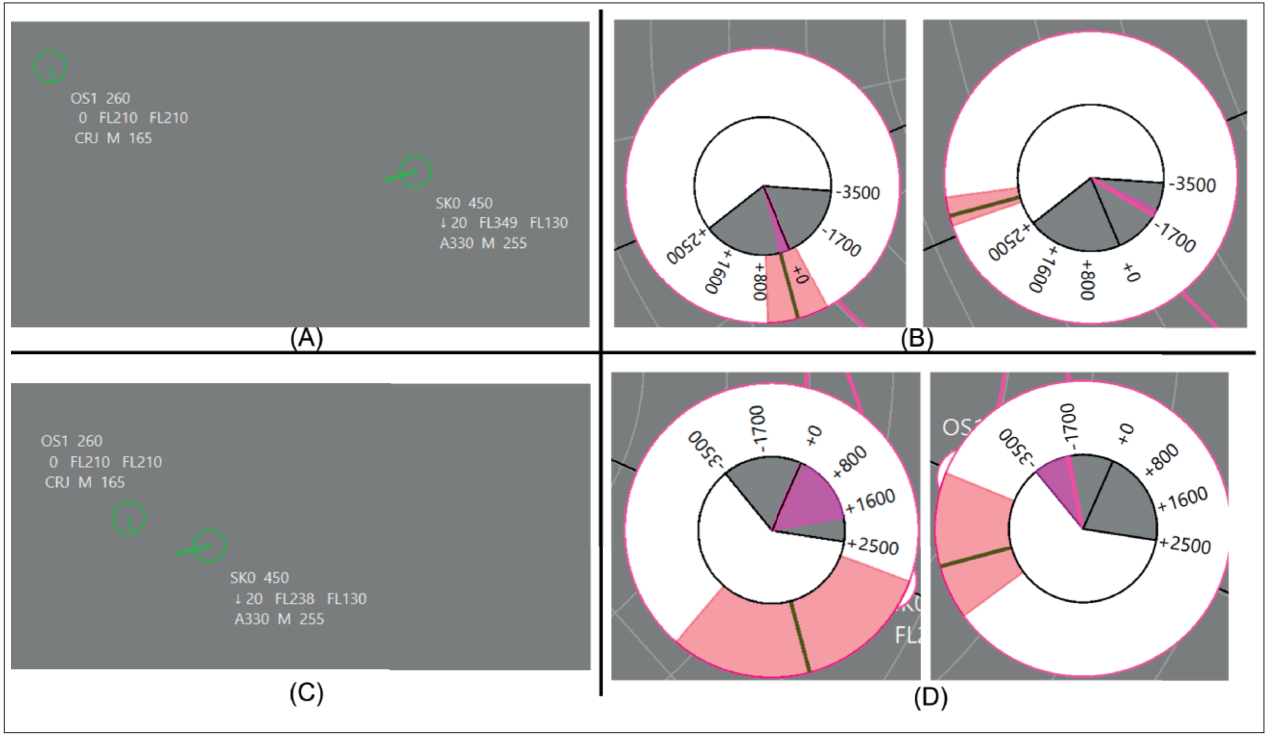

Figure 5.1: Conflict progression as shown on a simulated version of the currently used displays (A and C) and the ATL-Viz composite glyph (B and D). The top row (A and B) shows the situation a couple of minutes before loss of separation while the bottom row (C and D) represents seconds prior to loss of separation.

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A

Study Materials

A.1 Paper I: the HTA-Viz prototype

A.1.1 Confirmation of understanding checklist

The following presents the checklist I designed and used after the training session to make sure each participant has learned all the visual encodings successfully before start to participate in the simulation study.

Information provided by the visualization concepts on the radar display

1- Do you have good understanding of information shown on aircraft labels and the green line in aircraft icon?

2- Could you tell the difference between colorful and dark-shaded arc sectors?

3- Could you conveniently select an aircraft, change speed and heading?

Information provided by visualization concepts on the TA display

4- Could you find conflicting aircraft vertical profile, flight phase, time remaining to conflict and current flight level?

5- Could you explain what information the visualization for forbidden altitudes represents? and why some aircraft on radar display become red upon clicking on an aircraft icon on the TA display?

Interaction with the radar and the TA display

6- Could you conveniently report the aircraft pair you have detected?

7- Could you conveniently select an aircraft on the radar and the TA display?

8- Could you conveniently change aircraft speed and altitude?

A.1.2 interview session

The following presents the questions I asked ATCos at the semi-structured debriefing session which was performed after their participation in the simulation study.

Q1

How useful did you find the time-altitude (TA) visualization in terms of?
Please use a value between 0, 1, 2 and 3 for not at all, very little, somehow useful and very useful respectively.

- locating conflicts
- recognizing type of conflict
- prioritize conflicts to be solved
- workload increase/decrease
- reacting faster to conflicts
- finding solutions quicker

Please feel free to add more details about your opinion.

Q2

How did having either or both Heading Solution Space (HSS) and the TA visualizations visible, affect your task of conflict detection and resolution?
Did you detect and resolve conflicts more efficiently when (HSS/TA/neither/both) visualization were visible?

Q3

For which type of conflicts, if any, do you consider (HSS/TA/neither/both) visualization to be helpful?

Q4

To what extent do you think the HSS and the TA visualizations changed your way of thinking and problem solving?

Q5

What type of ATC tasks do you find visualizations less useful for and why? (e.g. monitoring, conflict detection and resolution, prioritization, plan, . . .)

As a follow-up question, which types of air traffic control do you find the tool mostly appropriate for and why? (ACC; area control or APP; approach and departure control)

Q6

Do you think the tool could be useful for future air traffic control? Which features of the tool do you find important and useful the most?

Q7

Did you find the tool trustworthy? How do you think the tool can be made more trustworthy?

A.2 Paper II: the ATL-Viz interface

A.2.1 User study

The following presents the questions I asked ATCos during the user study I conducted with two ATCos on a sample scenario shown on the preliminary prototypes of ATL-Viz and RAD-Viz.

1. Exploring the information needed for decision-making

1.1- What information do you need to detect conflicts?

1.2- What information do you need to prioritize and plan for solving conflicts?

1.3- What information do you need to solve conflicts?

1.4- What goals do you have when solving a conflict?

1.5- Do you need different set of information to solve different kinds of conflicts? (based on conflict geometry)

1.6- What information do you need to become certain about your choice?

2. Exploring information visualization support of the current ATC systems

2.1- How do you access the information needed to detect a conflict on the current system?

2.2- How do you access the information needed to prioritize and plan for solving conflicts on the current system?

2.3- How do you access the information needed to solve a conflict on the current system?

2.4- How do you access the information needed to become certain about your choice on the current system?

3. Exploring information visualization support of my designed interfaces
3.1- How do you access the information needed to detect a conflict on the ATL-Viz/RAD-Viz?
3.2- How do you access the information needed to prioritize and plan for solving conflicts on ATL-Viz/RAD-Viz?
3.3- How do you access the information needed to solve a conflict on ATL-Viz/RAD-Viz?
3.4- How do you access the information needed to become certain about your choice on ATL-Viz/RAD-Viz?

4. Exploring understandability of my designed interfaces
4.1- Please rank the visual interfaces in terms of easy to understand (from 1 being the easiest and 5 being the most challenging)
4.2- What features of the interface makes it the easiest to understand and why?
4.3- What features of the interface makes it the most difficult to understand and why?
4.4- What were your concerns when using this interface?

5. Exploring the ATCO's problem-solving strategies
5.1- Which parameters do you consider for making decision about a specific conflict?
5.2- Which parameters are more important for you? (e.g. time to conflict, flight phase, distance to airport, number of aircraft in the vicinity, conflict angle, vertical traffic in the vicinity) can you sort them?
5.3- How would you find the conflicts in this scenario? Please report the conflicts you detect
5.4- How do you plan to solve the conflicts? How long ahead do you plan?
5.5- How would you solve these conflicts and why? If the resolution is altitude change, what is the altitude buffer you use? If the resolution is ROC change, how do you make use of the info on the display to assign speed and ROC limitations during your command? What is your goal for this decision? Do you think your choice might lead to a potential conflict with any other aircraft? (if yes, with which aircraft? And how do you plan to solve that one?) How would you rate the difficulty of solving this conflict? What was the most challenging task in solving this conflict?
5.6- How does the interface support you in finding a viable solution for the conflicts?
5.7- How does the interface support you in finding an optimal solution based on your goal?
5.8- How does the interface ensure you that your solution will not lead to a potential conflict?

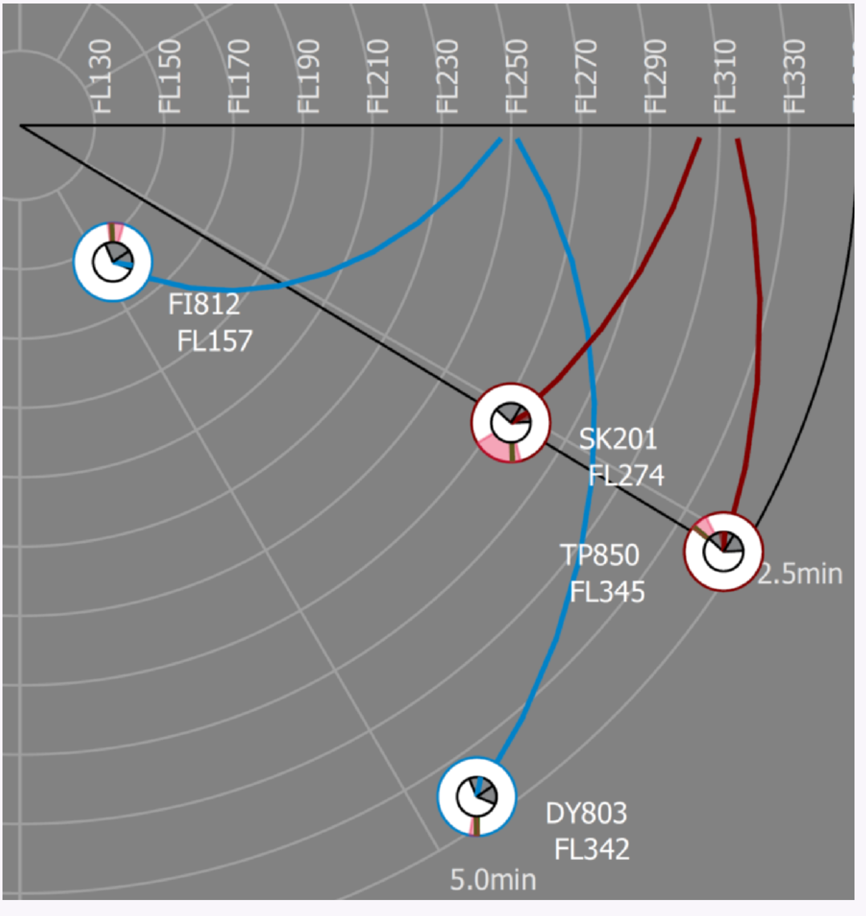
A.2.2 Design of the questionnaire

The following are questions I designed for the questionnaire study conducted with both ATCos and novices. For each group of participants (ATL-Viz or RAD-Viz), each question was asked once on the VA interface and once on the simulated version of current ATC systems. Here, the questions asked for ATL-Viz are presented.

Q1

At which FL is the aircraft "FI812" and "DY80" are predicted to lose separation?

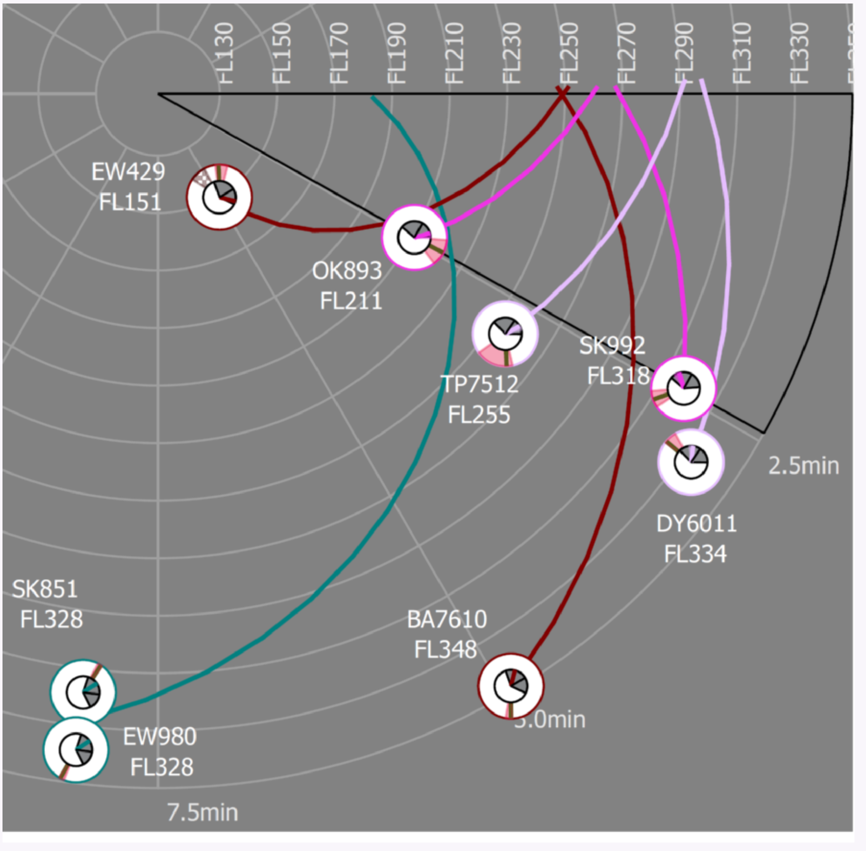
A: 150, B: 210, C: 250, D: 270, E: 310, F: 350



Q2

Which aircraft in conflict is flying at the highest FL?

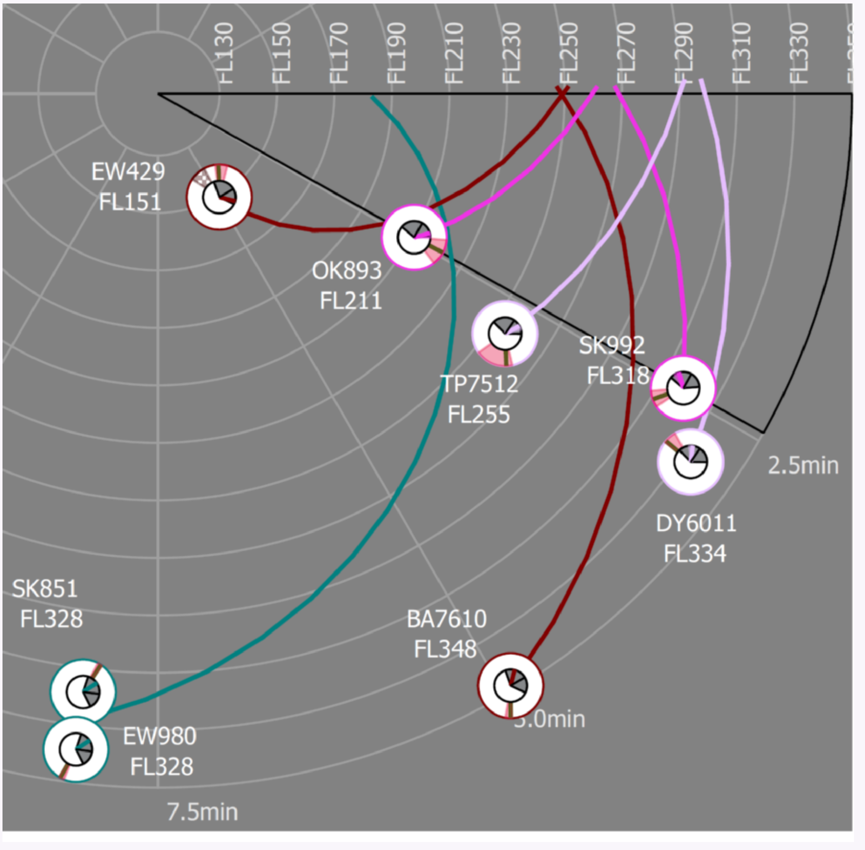
A: EW429
B: OK893
C: TP7512
D: SK992
E: DY6011
F: BA7610
G: SK851
H: EW980



Q3

Which aircraft in conflict is flying at the lowest FL?

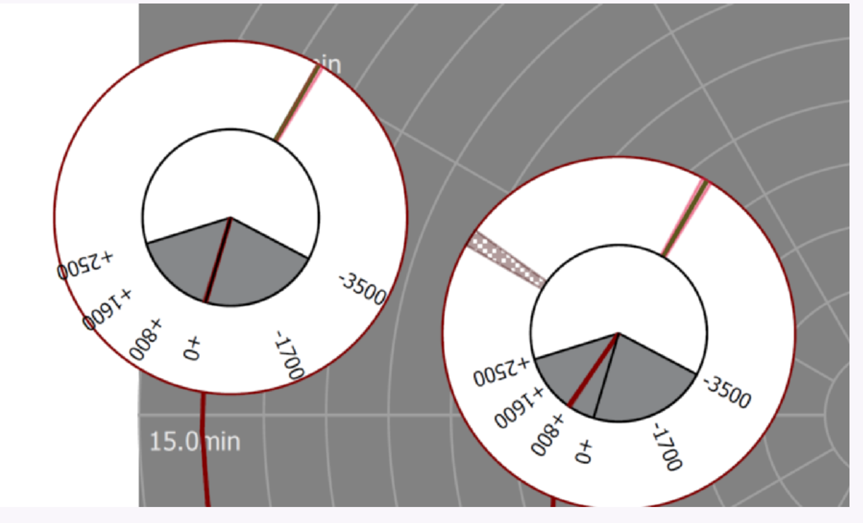
A: EW429
B: OK893
C: TP7512
D: SK992
E: DY6011
F: BA7610
G: SK851
H: EW980



Q4

What is the conflict geometry between these two aircraft?

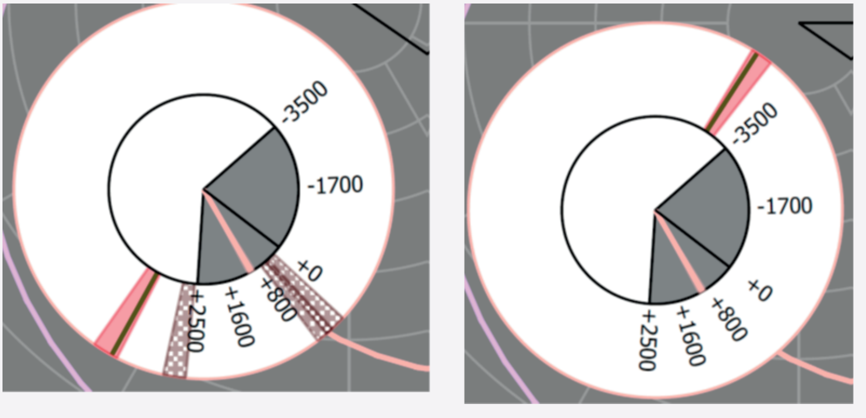
A: Both cruising/one chasing the other
B: Both climbing/flying towards each other
C: Climb-cruise/one chasing the other
D: Climb-cruise/flying towards each other
E: Descend-cruise/one chasing the other



Q5

What is the conflict geometry between these two aircraft?

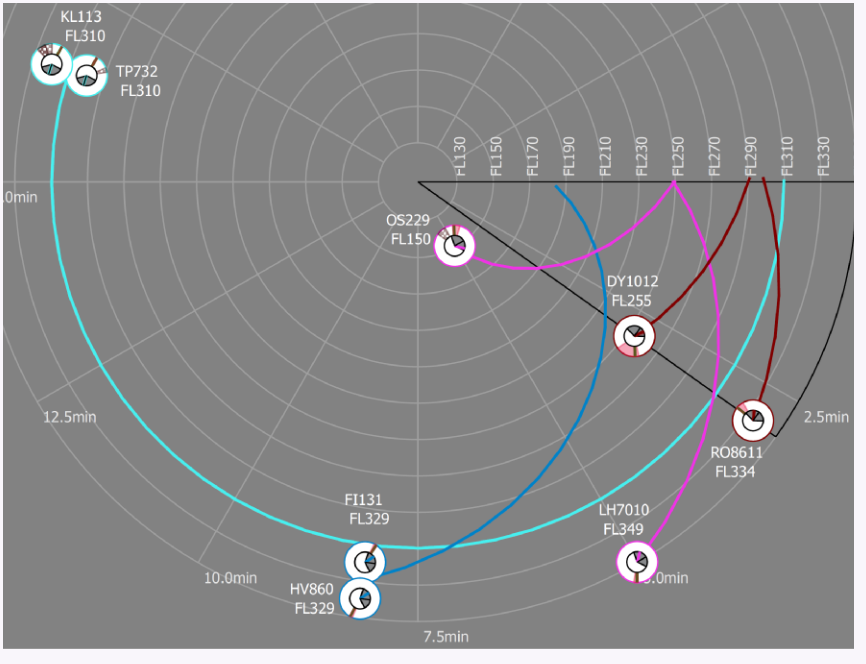
A: Both cruising/one chasing the other
B: Both climbing/flying towards each other
C: Climb-cruise/one chasing the other
D: Climb-cruise/flying towards each other
E: Descend-cruise/one chasing the other



Q6

Which aircraft pair in conflict is the most urgent?

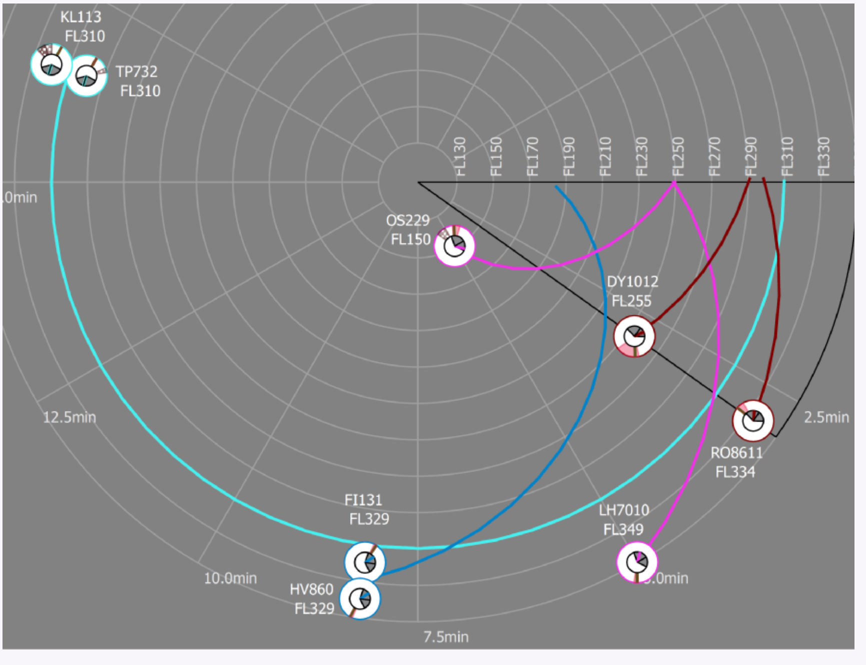
A: Cyan: KL113-TP732
B: Pink: LH7010-OS229
C: Blue: FI131-HV860
D: Red: RO8611-DY1012



Q7

Which aircraft pair in conflict is the least urgent?

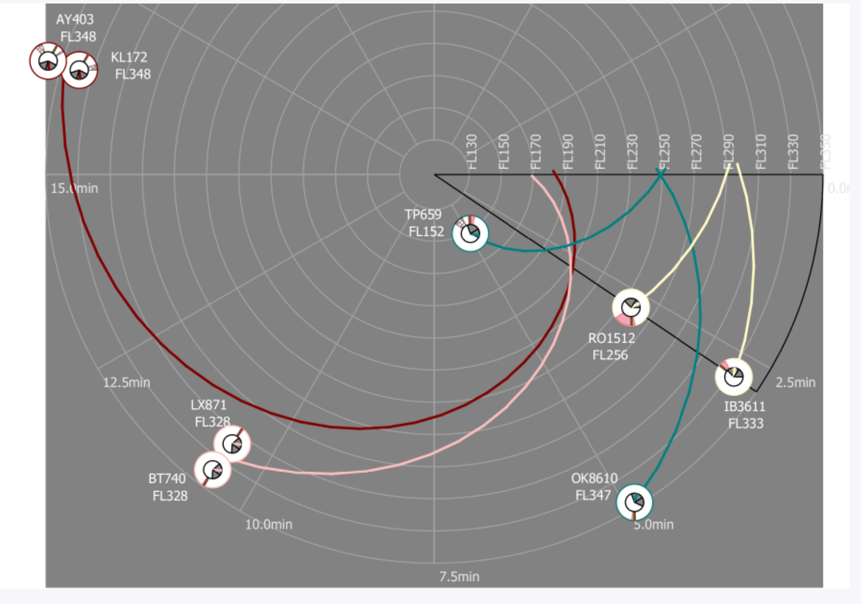
A: Cyan: KL113-TP732
B: Pink: LH7010-OS229
C: Blue: FI131-HV860
D: Red: RO8611-DY1012



Q8

Within the next 6 minutes, which aircraft will lose separation in-between FL260-FL310?

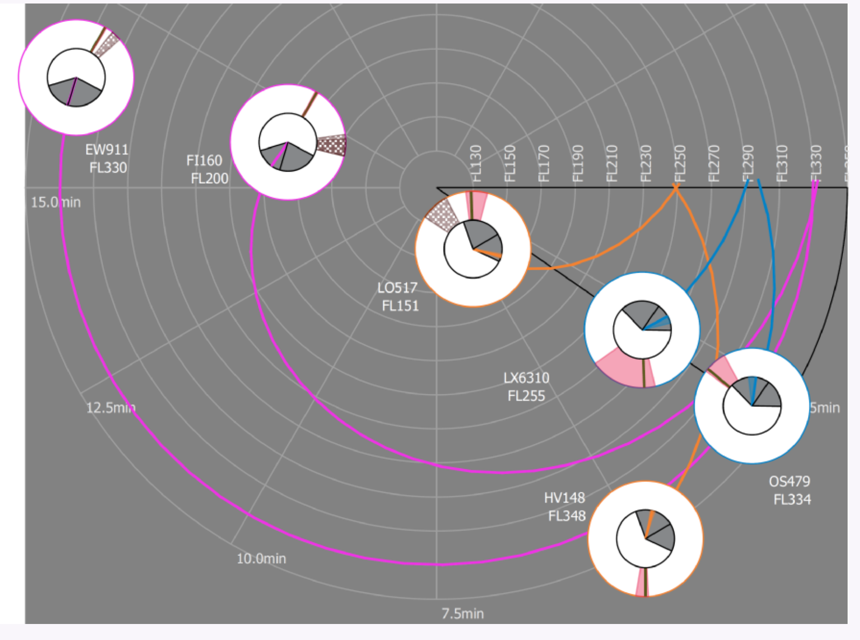
A: Green and yellow: TP659-OK8610 and RO1512-IB3611
B: Green and pink: LX871-BT740 and TP659-OK8610
C: Yellow: only RO1512-IB3611
D: Green: only TP659-OK8610



Q9

Which aircraft has the largest rate of climb?

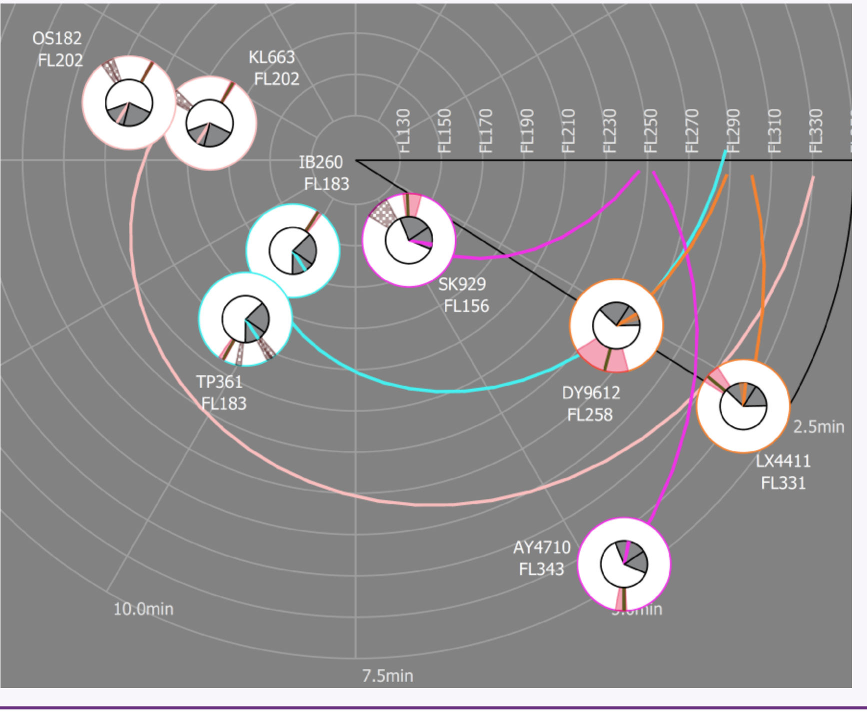
A: EW911
B: FI160
C: LO517
D: LX6310
E: HV148
F: OS479



Q10

Which aircraft requires the largest heading change in order to solve the conflict?

A: OS182
B: KL663
C: IB260
D: TP361
E: SK929
F: DY9612
G: LX4411
H: AY4710



A.3 Paper III: The novice-expert comparison

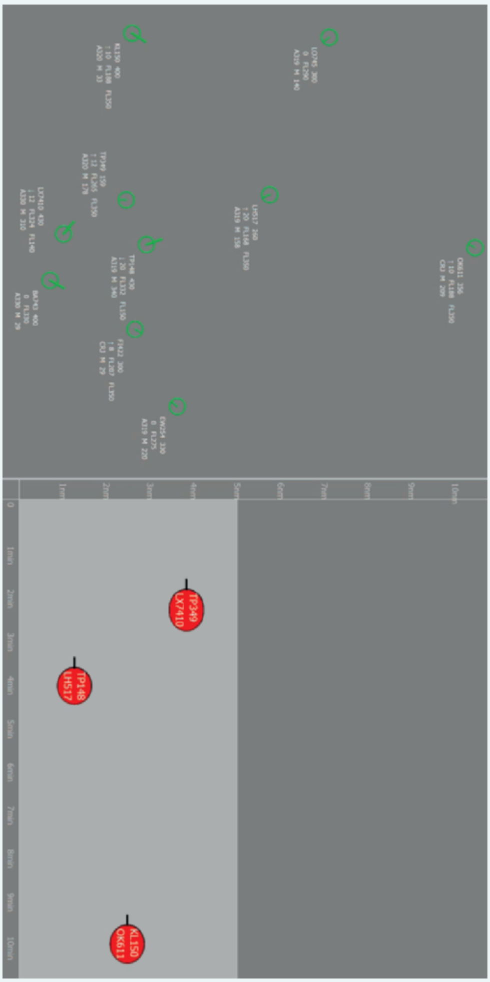
The following are questions designed to be used as a confirmation of understanding during the training session with novices. Here, only the questions asked from the RAD-Viz novices are presented.

Q1, Q2, Q3

Q1- How much time is remaining for the aircraft pair KL150 and OK611 to lose separation? A: 4 minutes, B: 6 minutes, C: 10 minute

Q2- At what rate is aircraft LH517 climbing? A: 2000 ft/min, B: 1200 ft/min, C: 1000 ft/min, D: 800 ft/min

Q3- Which aircraft is cruising at constant flight level? A: OK611, B: EW254, C: LH517, D:KL150



Q4, Q5, Q6

Q4- In this picture of the TA display, which aircraft are climbing?

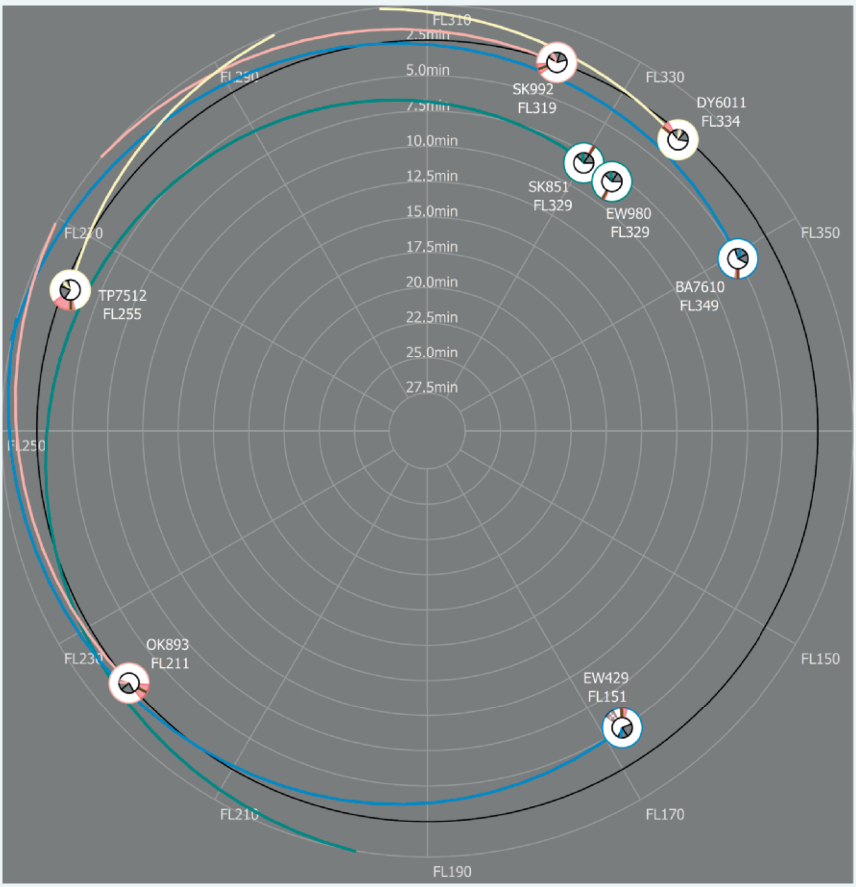
A: EW429, OK893 and TP7512,
B: BA7610, EW980 and SK851,
C: TP7512, DY6011 and OK893

Q5- At which flight level would the aircraft pair "EW429" and "BA7610" lose separation?

A: FL180, B: FL260, C: FL290

Q6- When will aircraft pair "SK851" and "EW980" lose separation?

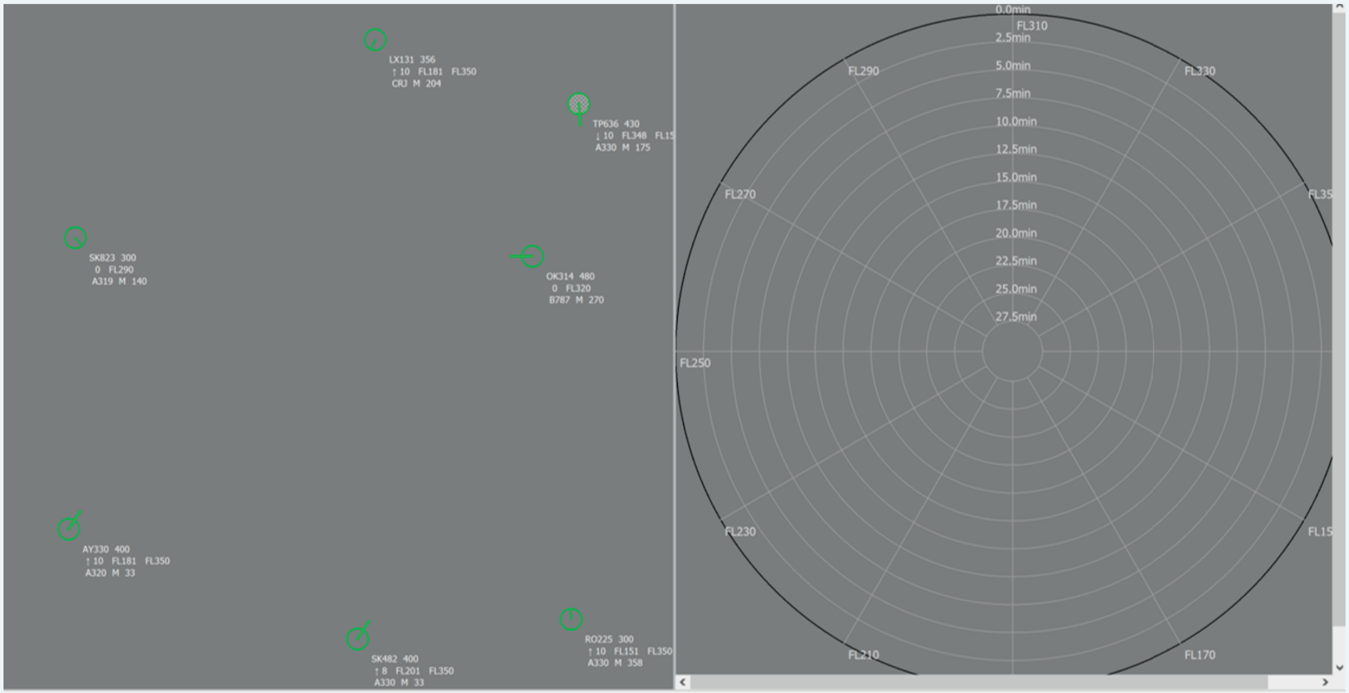
A: In more than 7 minutes, B: In 5 minutes, C: In 3 minutes



Q7

Knowing that there are no aircraft displayed on TA display, which sentence is correct?

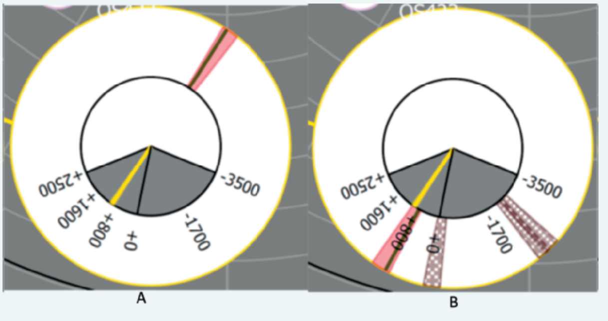
A: No aircraft is climbing
B: No aircraft is flying
C: No aircraft is selected
D: There are no conflicts



Q8

Which value is a good estimation of aircraft A heading in this conflict?

A: 90 degrees, B: 20 degrees, C: 300 degrees, D: 270 degrees



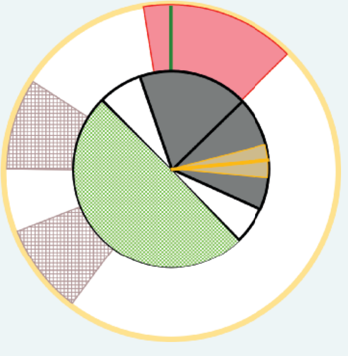
Q9, Q10

Q9- What information does the brown patterned section represent?

A: If the heading is selected in that area the current conflict will be solved but a new conflict with another aircraft will be created.
B: Conflict-free choices for rate of climb change
C: Conflict-free choices for heading change

Q10- What information does the colorful area inside the grey area represent?

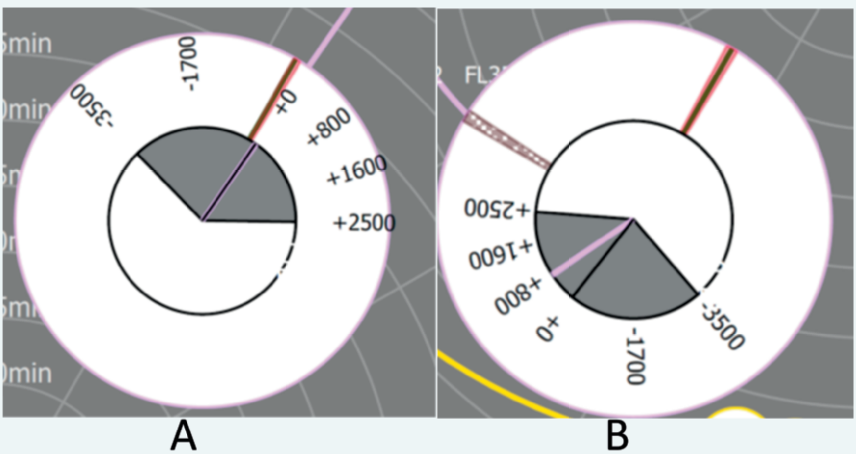
A: If the heading is selected in that area the current conflict will be solved but a new conflict with another aircraft will be created.
B: If rate of climb is selected in that area the current conflict will not be solved.
C: If the rate of climb is selected in that area the current conflict will be solved.



Q11

Which value is a good estimation of the rate at which aircraft B is climbing or descending?

A: 850 ft/min
B: -1750 ft/min
C: Aircraft B is cruising
D: 2500 ft/min



Q12, Q13, Q14

Q12- Which of the following decisions will resolve the conflict between the aircraft A and B?

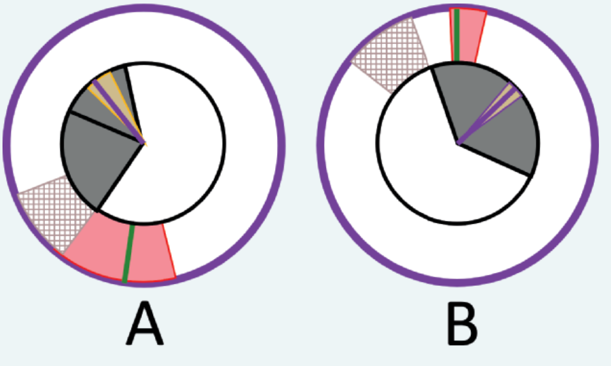
A: Changing aircraft A rate of climb inside yellow area
B: Changing aircraft B heading inside the red area
C: Changing aircraft B rate of climb inside the grey area

Q13- Which of the following sentences are correct?

A: Changing aircraft B's heading to the closest value inside the white area leads to less deviation than changing aircraft A's heading.
B: There is only one solution to this conflict: changing one aircraft's rate of climb.
C: Aircraft A is cruising (its rate of climb is zero)

Q14- Which of the following sentences are correct?

A: The two aircraft are in conflict and are heading towards each other horizontally
B: The two aircraft are in conflict and one aircraft is chasing the other horizontally
C: Aircraft B's heading is around 180 degrees



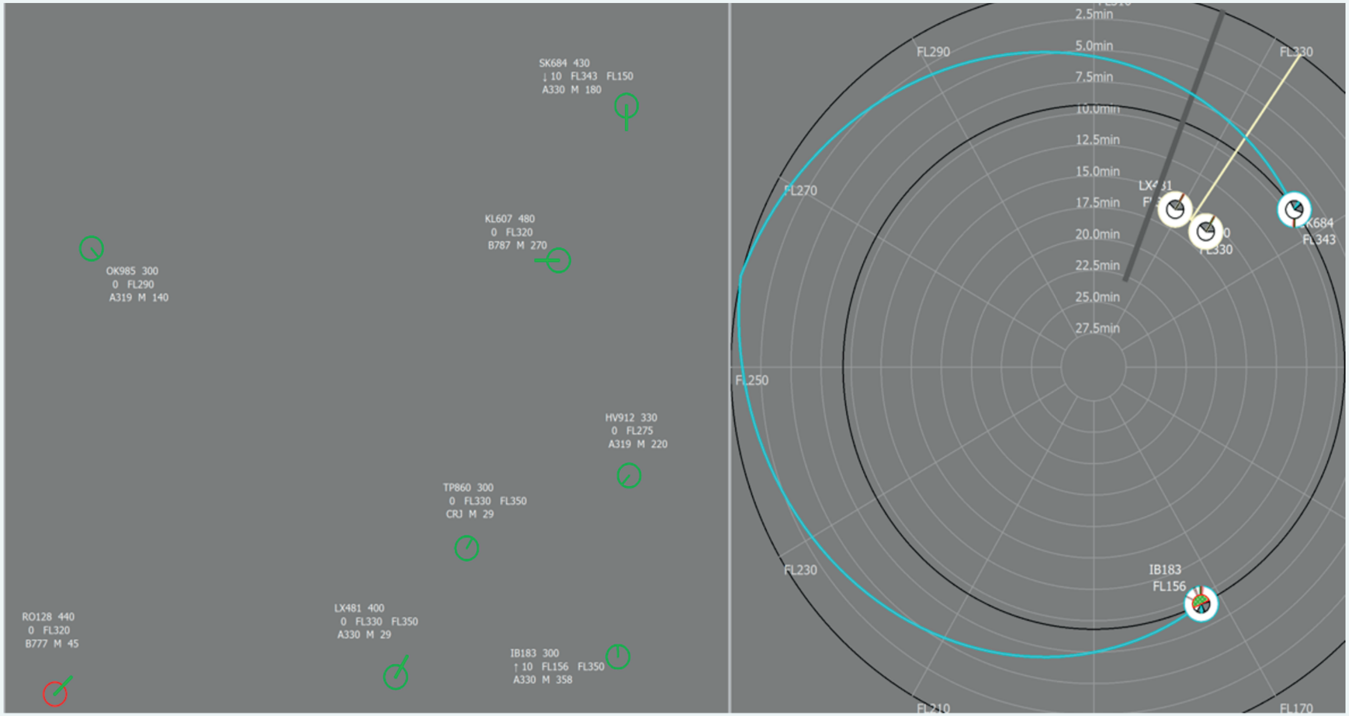
Q15

What information does the grey line represent?

A: IB183 is selected

B: If aircraft IB183 (selected) is sent to FL320 it will have conflict with RO128

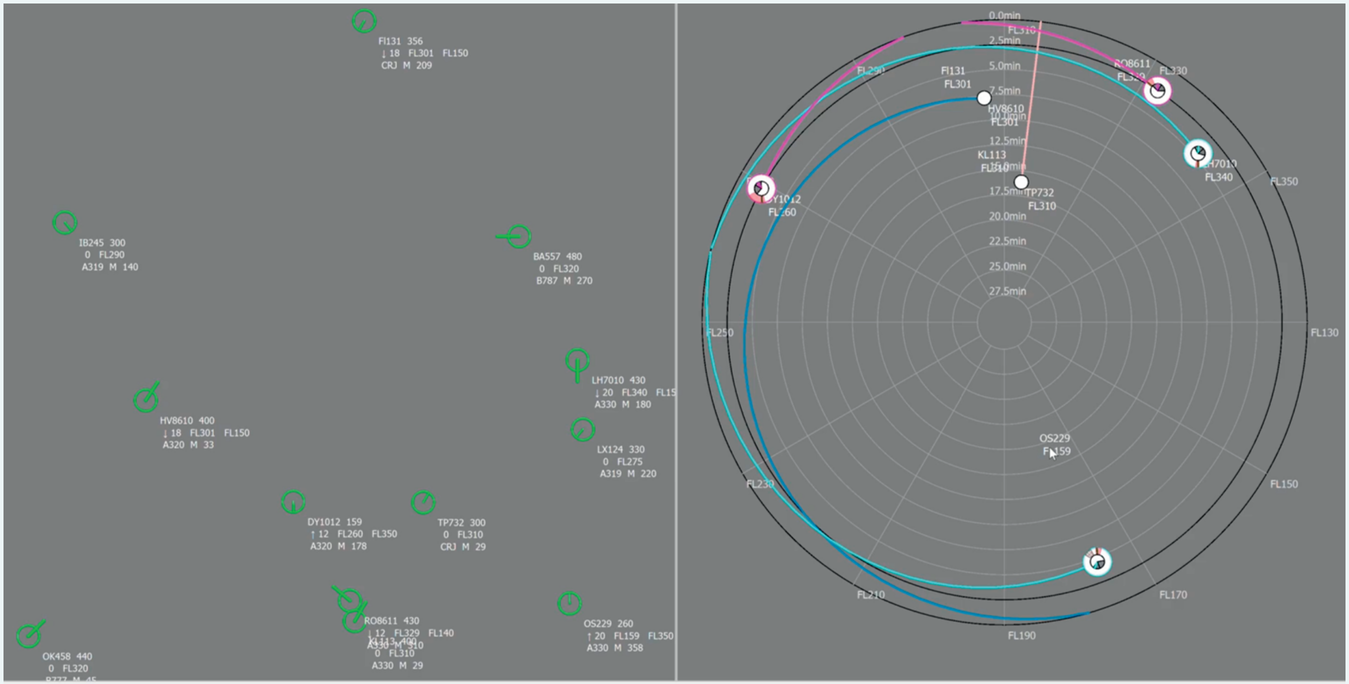
C: IB183 is now in conflict with RO128



Q16

How many conflicts are there in the following scenario?

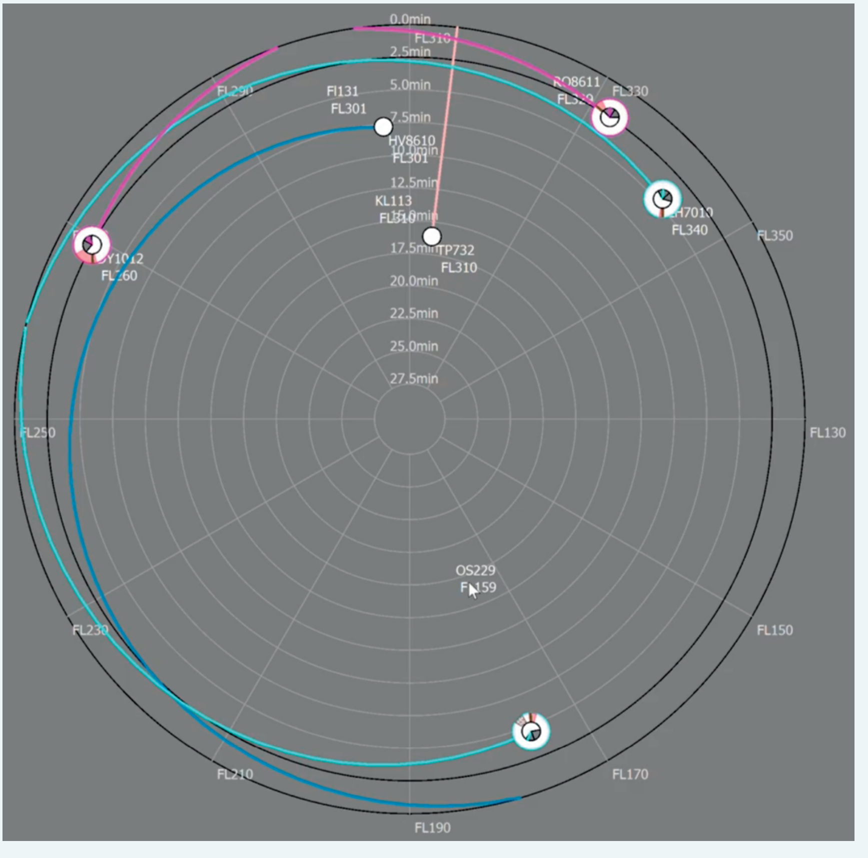
A: 4 (As TA is showing 4 pairs in conflict)
B: 3 (As TA is showing 3 pairs in conflict)
C: 5 (4 on TA and one on the left display)



Q17

Which of the following decisions will resolve the most urgent conflict? (between RO8611 and DY1012)

A: Sending RO8611 to FL320
B: Sending RO8611 to FL300
C: Sending DY1012 to FL305



A.4 Paper IV: the ATLViz-cplx interface

The following presents the questions I asked ATCos at the qualitative study session after their participation in the simulation study.

Q1

How useful did you find the complexity visualization in terms of?
Please use a value between 0 to 7 for not at all, somehow useful, and very useful respectively.
- Detecting complex patterns and showing their complexity level
- Comparing cluster complexity sensitivity to each aircraft
- Traffic disorder change upon heading and speed changes inside the glyph
- reacting faster to complex clusters
- Finding solutions quicker

Please feel free to add more details about your opinion.

Q2

For which type of traffic patterns do you consider the visualization to be helpful?

Q3

To what extent do you think the visualizations changed your way of thinking and problem solving?

Q4

Do you think the tool could be useful for future air traffic control? Which features of the tool do you find important and useful the most?

Papers

The papers associated with this thesis have been removed for copyright reasons. For more details about these see:

https://doi.org/10.3384/9789179294908

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