DOI: 10.1111/cgf.14431

COMPUTER GRAPHICS *forum*
Volume 41 (2022), number 1 pp. 230–242

Design and Evaluation Study of Visual Analytics Decision Support Tools in Air Traffic Control

E. Zohrevandi, C. A. L. Westin, J. Lundberg and A. Ynnerman

Department of Science and Technology, Linköping University, Norrköping, Sweden
{elmira.zohrevandi, carl.westin, jonas.lundberg, anders.ynnerman}@liu.se

Abstract

Operators in air traffic control facing time- and safety-critical situations call for efficient, reliable and robust real-time processing and interpretation of complex data. Automation support tools aid controllers in these processes to prevent separation losses between aircraft. Issues of current support tools include limited 'what-if' and 'what-else' probe functionalities in relation to vertical solutions. This work presents the design and evaluation of two visual analytics interfaces that promote contextual awareness and support 'what-if' and 'what-else' probes in the spatio-temporal domain aiming to improve information integration and support controllers in prioritising conflict resolution. Both interfaces visualize vertical solution spaces against a time-altitude graph. The main contributions of this paper are: (a) the presentation of two interfaces for supporting conflict solving; (b) the novel representation of how vertical information and aircraft rate of climb and descent affect conflicts and (c) an evaluation and comparison of the interfaces with a traditional air traffic control support system. The evaluation study was performed with domain experts to compare the effects of visualization concepts on operator engagement in processing solutions suggested by the tools. Results show that the visualizations support operators' ability to understand and resolve conflicts. Based on the results, general design guidelines for time-critical domains are proposed.

Keywords: Human–computer interfaces, interaction, information visualization, visual analytics, visualization

CCS Concepts: • Human-centred computing → Visual analytics; visualization design and evaluation methods; • Hardware → Safety critical systems

1. Introduction

For operators of complex systems, handling time-critical events can be challenging. The mental workload associated with information processing exposes operators to a high risk of reduced and erroneous performance. Air traffic control (ATC) is an example of a complex environment where operators constantly need to read and analyse spatio-temporal data to maintain safe separation between aircraft. Supporting the operator with a real-time visual analytics (VA) tool in critical situations can support the operators' reasoning, analysis and problem-solving.

Conflict detection and resolution (CD&R) is a central and critical task for air traffic controllers (ATCos). ATCos ascertain safe separation by keeping aircraft apart with at least 5 nm (horizontal) or 1000 ft (vertical) distance. When dealing with conflicts they consider four dimensional (time, x, y, z) resolution spaces, which do not cause new conflicts. Despite this multidimensional problem, current ATC displays (i.e. the 'radar' display) have inherited an archaic $x - y$ horizontal position display, evolved from a traditional view of aircraft symbols being moved manually on a table top. These displays primarily visualize the horizontal relationship between aircraft, while leaving the vertical relationship for ATCos to mentally process. Modern displays can also provide information on which aircraft that is in conflict and where on their trajectories separation limits will be violated. Basic plots of time-to-conflict, conflict duration and distance between conflicting aircraft are typically available in separate graphs, i.e. a conflict and risk display (CARD).

One problem with current ATC systems is the lack of a visual interface that shows altitude-based solutions, allowing for effective decision support for urgent and difficult-to-solve situations. Research has shown that ATCos find conflict situations with a mix of climbing and descending aircraft the most challenging to resolve [RN05]. Willems *et al.* [WAS99] found that ATCos prefer flight level (FL) change as it requires the least monitoring effort to ensure safe separation between aircraft. Current systems do not predict conflicts if an aircraft is assigned to a new FL. According to Bole-Richard and Abert [BRA16], such limitations of current systems can result in high unwanted cognitive load for the ATCo.

This paper presents and evaluates two novel visual interfaces tailored for CD&R workflows, augmenting existing interfaces, and thus supporting ATCos in task prioritisation and decision-making. Since aircraft move and situations change, the representations must encode dynamic temporal data for real-time decision-making. The next section describes previous work on CD&R tools and techniques for glyph-based visualizations that have motivated designs of the two VA interfaces. Section 3 details the VA interfaces design. Section 4 presents a human-in-the-loop experiment assessing the two VA interfaces with fourteen licensed ATCos. Section 5 embodies the results and Section 6 discusses the study findings. Last, Section 7 lays out the concluded design guidelines for visualization of information for operators in time-critical domains.

2. Related Work

VA methods for spatio-temporal analysis of large data sets of aircraft trajectories have been studied thoroughly (e.g. [ALP12, ACS18, BTD14, BJA*15, HTC09, HCGT14, KVDZT14, MTH*16]). The methods rely on predictions that are made offline. They mainly support air navigation service providers and trajectory planners. Thus, these VA interfaces are not targeting ATC workflows with real-time critical decision-making situations.

Previous studies have focussed on supporting ATCos in CD&R decision-making by proposing novel interface design concepts. In Beernink *et al.* [BBE*15], a horizontal solution space diagram (SSD) concept [VDMVP08] originally developed for pilots, was introduced in an ATC display design. For a selected aircraft, the SSD visualizes the heading and speed constraints imposed by the surrounding traffic. Previous studies have found the SSD, and iterations thereof, to be more efficient in supporting ATCos decision-making than current ATC tools. For example, Mercado-Velasco *et al.* [MVMVP10] showed that the SSD diagram can reduce ATCos' workload, in particular in high traffic density situations. In the work of Borst *et al.* [BBVPM17], where the designed interface presented advisory solutions to CD&R, it was shown that the SSD concept improved ATCos' fault-diagnosis of the automated advice. The works of Lodder *et al.* and Mercado-Velasco *et al.* [LCVPM11, MVMVP10] developed versions of the SSD-based interfaces in which altitude-based solutions were proposed. Even though integration of vertical solutions is attempted in the aforementioned designs, the following important functionalities are missing. First, the altitude-based solutions proposed are limited to neighbouring FLs (not showing all possible solutions). Second, the information visualized was only available to ATCos on request. Therefore, simultaneous comparison of solutions between multiple aircraft was not possible. Third, since rate of climb or descent (ROCOD) solutions were not visualized, ATCos needed to infer such information.

Integration of both vertical and horizontal solution space information in current ATC tools, so that ATCos can compare possible resolution strategies, is challenging. Displaying more information can increase complexity in visual search and target detection [Xin07]. In the work of Beernink *et al.* [BBE*15], integrating more information to the original SSD design increased ATCos' workload and clutter in display. Moreover, if the way visual representations are organized is confusing to the operator, it may lead to misinterpretations of the data and a deterioration in task performance [Dur04, Joh02, RLMJ05].

In the field of visualization, glyph-based visualization is a common approach for integration of multidimensional data in a space-efficient way. The works of Borgo *et al.* and Ward [BKC*13, War08] have shown the potential benefits of glyph-based visualization. The technique enables users to effectively analyze complex data by encoding the information through different visual channels (e.g. shape, colour, size and orientation). A major strength of this is that glyphs facilitate perception of patterns in the data involving more than three dimensions.

Another limitation of previous approaches is that they do not support ATCos in task prioritisation. ATCos' decisions regarding temporal tasks (e.g. which task to handle first) influence their workload [Hil04, R*92]. It has been shown that the use of a clock metaphor can improve users' efficiency in finding patterns and performing temporal tasks [FFM12, FFM*13, KFM11].

In the current work, a glyph-based visualization approach is applied to the design of VA interfaces to visualize key aspects of solutions to conflicting situations (e.g. the vertical relationship between aircraft, what-if and what-else probes). Furthermore, using polar graph techniques, task prioritisation is considered in the design. The approach has enabled the use of the clock metaphor in one of the designed VA interfaces.

3. Design of VA Interfaces for ATC

The designs presented in this paper are based on the foundational experiences and results from the work of Zohrevandi *et al.* [ZWLY20], where a heading-time-altitude visual analytics (HTA-Viz) prototype was proposed. A pilot study on the HTA-Viz prototype, accounted for in Appendix 1, revealed two important design issues. First, in specific traffic situations when challenging (mixed-climbing and descending) and time-critical conflict situations occur simultaneously close to the loss-of-separation line, the TA display becomes cluttered, making it difficult to compare solutions between neighbouring glyph pairs. Second, ATCos could not closely examine the possible solutions for heading, the rate of climb or the rate of descent. Third, the design was not fail-proof against unintentional clicks of ATCos on the glyphs. These conclusions provide the starting point for the design of the two interfaces presented in this paper.

3.1. Design of ATL-Viz

Figure 1(a) presents a schematic representation of the angular time line visualization (ATL-Viz). ATL-Viz uses polar graph technique to highlight situation urgency and the vertical relationship between aircraft. Here, time is visualized as a clock (with loss of separation occurring at the 3 o'clock line). This way ATL-Vizs upports ATCos in prioritisation of which conflict to resolve first. Altitude is shown as distance from the midpoint (increasing outwards). Small circles represent aircraft glyph, the design of which is explained in

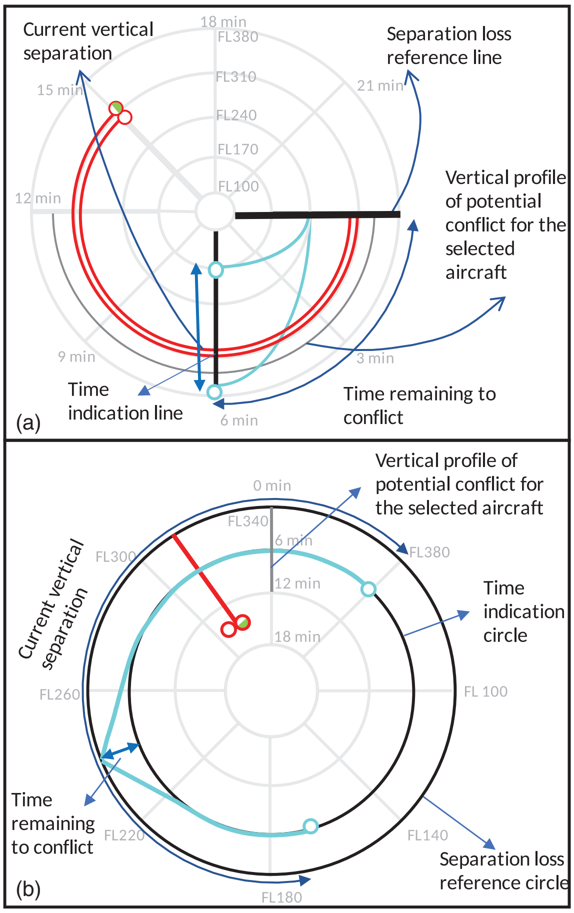

Figure 1: *Schematic comparison of (a) ATL-Viz and (b) RAD-Viz showing differences in how aircraft pair in conflict are visualized. Small circles represent aircraft glyph. In ATL-Viz, time and FL information are mapped on angular and radial axes of the polar graph while in RAD-Viz, the same information is visualized on inverted axes of the polar graph. The aircraft pair in cyan is the most imminent conflict pair, which will lose separation in 6 min at FL240. The less urgent conflicts (red aircraft) are both cruising at FL310 and will lose separation in 15 min.*

Section 3.3. The red aircrafts are both cruising at FL310, while the cyan aircraft pair is a mixed climb-descent conflict, which needs to be resolved urgently. Urgency of the conflict is emphasized by the black line passing the aircraft pair radially. As time passes, the line moves counterclockwise towards the separation loss reference line. The line position indicates time remaining to conflict, like the arm of a clock. The radial distance between two aircraft represents their vertical distance.

3.2. Design of RAD-Viz

A second visualization display called radial time visualization (RAD-Viz) was developed. The design was motivated by a need to explore the effect of an alternative visual representation of the temporal domain. The main difference between the ATL-Viz and RAD-Viz is how information is organized (i.e. inverted) on the time and altitude axes (see Table 1).

Table 1: *Data mapping description for angular time line visualization (ATL-Viz) and radial time visualization (RAD-Viz).*

Data	ATL-Viz	RAD-Viz
Time remaining to conflict	Angular axis (clockwise) Measured from: radial line at 3 o'clock	Radial axis (inwards)Measured from: outermost circle
Flight level	Radial axis (outwards) Measured from: graph centre	Angular axis (clockwise) Measured from: radial line at 3 o'clock

Notes: ATL-Viz: angular time line visualization; RAD-Viz: radial time visualization.

Figure 1(b) presents a schematic representation of RAD-Viz. In RAD-Viz, time is visualized on the radial axis from the inside-out, with separation losses occurring at the outer edge (separation loss reference circle). A black circle (time indication circle) highlights the most imminent conflict pair (the cyan aircraft pair) at the 6-min mark. The position on the circle indicates the altitude of the aircraft in FL. The top-right aircraft is on the FL380 line and the other aircraft is on the FL170 line. We see that the conflict will occur at FL240, as the cyan lines meet there. In contrast, the less urgent (15 min) red aircrafts are both cruising, resulting in their vertical profiles being represented as straight red lines inside-to-out.

3.3. Glyph design for both VA interfaces

To integrate solution space information to ATL-Viz and RAD-Viz, a composite glyph was designed. The starting point for the glyph design was the previous work of Zohrevandi *et al.* [ZWLY20], where heading solution spaces (HSS) were visualized in the outer circle and ROCD solutions were visualized inside the inner circle; see Figure 2.

In this work, the glyph additionally displays a rich ROCD representation where, HSS and ROCD conflict and solution zones can be encoded more clearly. To improve glyph interaction and support rapid comparison of resolution strategies, a mouse-hover functionality was added to glyphs. When hovering over a glyph, the glyph size increases to provide more detailed solution spaces. Figure 3 presents the composite glyph and its components. On the outer circle, heading conflict zone is shown with the red section (current conflicts) and the patterned section (potential conflicts). The white section represents HSS. On the inner circle, the green half circle indicates that the glyph is selected. The colourful section (on top of the grey section) represents ROCD conflict zone, making the grey zone ROCD solution space. To better distinguish glyphs in a conflict, the outer circle colours were changed to the colour of aircraft vertical profile. ROCD values were written near the outer border of the ROCD range to enhance readability. Figure 3 also shows how the improved interaction was accomplished in two steps. First, various heading and ROCD values can be explored by right-clicking inside the outer and inner circle respectively. A dashed line inside the circles indicates the selected value. Then, when left-clicking inside the outer circle, a confirmation box appears. For the change to

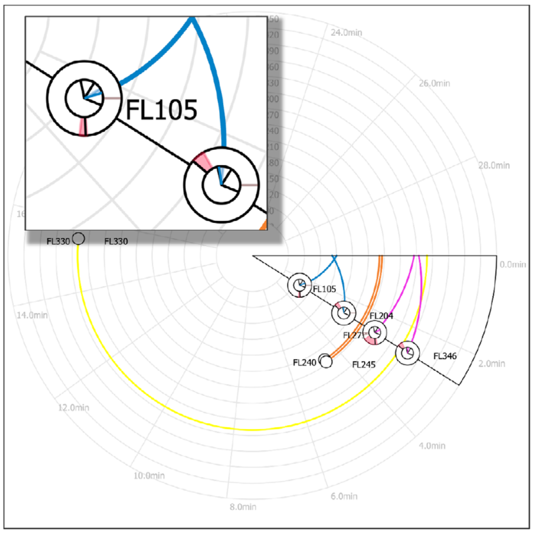

Figure 2: *HTA-Viz: Aircraft is represented by a glyph, and radial distances indicate altitude. From each glyph, a line indicates the altitude at the time of conflict. Each glyph has two onion-skin layers. The inner layer shows rate of climb or descent (ROCOD) in three black lines: middle line equals level flight, right line shows maximum ascent and left line shows maximum descent. The black line in the outer layer shows the current heading. The black lines of both aircrafts are inside a coloured conflict, but both are at the edge of the conflict zone, suggesting that a small change will resolve the conflict.*

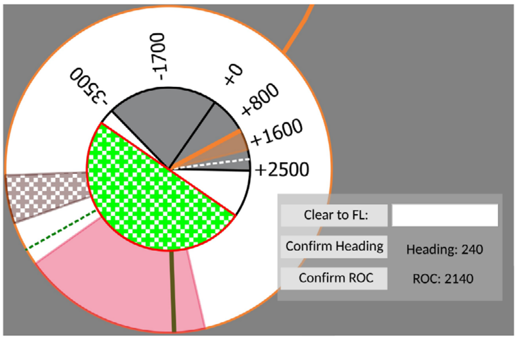

Figure 3: *Interactive features in the finalized composite glyph design. Red and patterned sections inside the outer circle represent current and potential heading conflict zones. The grey zone inside the inner circle represents rate of climb or descent (ROCD) solution space, and the coloured section on top of it represents ROCD conflict zone. The green semi-circle is used to select the aircraft. Dashed lines show the selected values in the glyph. The exact value can be seen in a confirmation box, which appears next to the glyph when left-clicking inside the outer circle. A heading value selection inside the patterned section indicates occurrence of a potential conflict (what-if probe).*

take effect, the ‘Confirm Heading’ or ‘Confirm ROC’ button must be pressed.

Figure 4 presents the ATL-Viz and RAD-Viz interfaces with aircraft glyphs for the same traffic scenario. Coloured curves show vertical trajectory profiles for the aircraft pair in conflict. The dark grey curve shows the vertical profile of a potential conflict for the selected aircraft, emphasising altitude-based solutions.

The pointer here hovers over a descending aircraft of the most urgent conflict. As can be seen from Figure 4, when multiple imminent and challenging (mixed climb-descent) conflicts occur, the ATL-Viz becomes cluttered, whereas in the RAD-Viz, the FL distance is visualized more spread out as conflicts become more urgent. This can be an advantage of mapping time over the radial axis (as visualized by RAD-Viz). In the glyph design of ATL-Viz, the area in front of the time indication line is used to visualize ROCD solution spaces and the area behind the time line is used to select the aircraft. In the design of RAD-Viz, the area outside the time indication circle is used to visualize the ROCD solution space, and the area behind the circle is used to select the aircraft. Since time and altitude information is mapped on ATL-Viz and RAD-Viz over different axes, rotation angles for the inner circle of composite glyph will differ between the two visualizations. However, HSS visualizations are identical in the two representations.

The designed interfaces support ATCos in probing what-else and what-if functionalities. The what-else functionality consists of simultaneous visualization of all three combined solution spaces in the composite glyph (heading and ROCD) and the time-altitude display (altitude solution space). Thus, they can visually compare one solution idea to the others (what ELSE: what other resolution strategy they could choose). The what-if functionality consists of visualising conflict zones for both current and potential conflicts, depending on the value selected, if selecting a specific resolution. As can be seen in Figure 3, the patterned section of the outer circle indicates resolution of the current conflict but occurrence of a potential conflict if heading is selected within the specified range. The dark grey path shown in Figure 4 (circular curve in ATL-Viz and straight line in RAD-Viz) indicates that a potential loss of separation will occur in approximately 7 min7 if the selected aircraft is sent to FL320. The algorithms derived for calculation of both horizontal and vertical solution spaces presented in Zohrevandi *et al.* [ZWLY20] are used in the design and implementation of both ATL-Viz and RAD-Viz.

4. Method

A study was conducted to evaluate the effects of the VA interfaces on ATCos’ understanding and decision-making for aircraft pairs in conflict. The experiment consisted of two parts: Study 1 and Study 2. Fourteen ATCos (1 men and four women) participated in the study. Average age was 43.6 (SD = 8.97, range 22–60 years) and average experience 19.5 years (SD = 7.48, range 8–35 years). Nine had en-route experience; four had approach control experience; one had both. Participants were divided into two groups of seven: one for each VA interface.

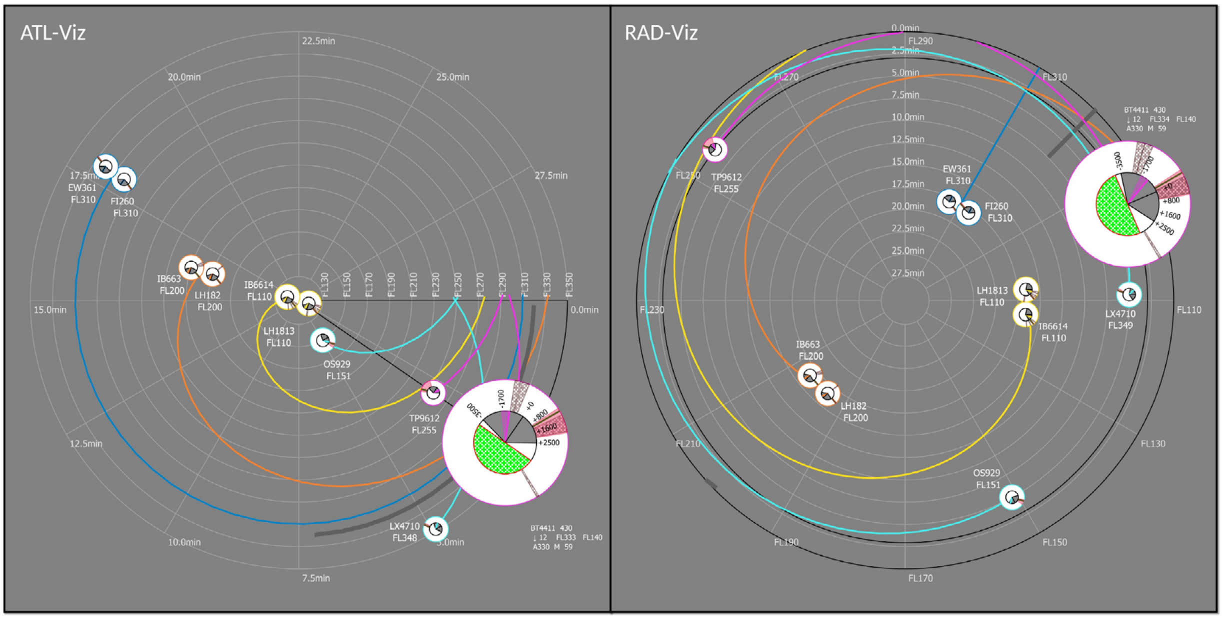

Figure 4: *Example of angular time line visualization (ATL-Viz) and radial time visualization (RAD-Viz) depicting the same traffic situation. The air traffic controller (ATCo) can visualize consequences for their decisions (what-if probe) and compare all solutions on both visualizations (what-else probe).*

4.1. Experiment control condition

A reference design was implemented based on currently used displays: a conventional 2D horizontal traffic visualization ('radar screen') and a CARD display (see fig. 2 in Lundberg *et al.* [LSJ*15]). The radar screen was shown in all display conditions. Each aircraft was represented on the radar screen with a circle and a line indicating horizontal direction. Each aircraft also had a movable text label showing basic aircraft state information. Heading change values could be explored inside the aircraft glyph on the radar screen. A confirmation box would appear on the radar screen by double-clicking on the aircraft label, enabling the ATCo to change ROCD and FL on the radar screen. Aircraft speed could be changed by pressing 'Q' and 'W' buttons on the keyboard. The CARD display represented the control condition. On the CARD display, the labels showed aircraft pair in conflict with time and distance remaining to separation loss. Similar to currently used displays, interaction with aircraft was not possible on the CARD display.

4.2. Research questions

Three research questions were identified:

1. RQ1: To what extent does focus + context visualization of in-conflict pairs and their solution spaces affect ATCos' effectiveness in understanding the information of aircraft in conflict?
   A comparison was made between the VA interfaces as they both featured focus + context visualization of solution spaces, and the control display as it did not show any information about solutions to conflicts. To evaluate effectiveness, we measured ATCos' completion time for tasks, and accuracy in providing the correct answer. Accuracy was measured as error rate. (i.e. percentage of ATCos choosing a wrong answer to the task).
2. RQ2: To what extent does focus + context visualization of in-conflict pairs and their solution spaces affect ATCos' decision-making process about aircraft pairs in conflict?
   The following parameters representing decision-making process were measured: time to engage in interaction with conflicts; time to resolve conflicts; subjective workload; choice of resolution strategies and display(s) interacted with to resolve conflicts. To evaluate glyph effectiveness, number of ROCD or heading resolutions made on the glyph or in the radar display, was measured.
3. RQ3: To what extent does the mapping visualization of the temporal domain on angular coordinates and vertical movement of aircraft on radial coordinates, using a polar graph technique (in ATL-Viz), affect ATCos' performance in prioritising conflicts?

The number of conflicts resolved by ATCos in the actual order of urgency (time-to-conflict) was measured to explore the effect of the metaphoric (i.e. the clock metaphor) temporal visualization of aircraft movement data on the angular axis of polar graph.

4.3. Study 1: understandability assessment

The first study evaluated participants' effectiveness in understanding the information about in-conflict pairs. This part consisted of a mixed-study design with three independent variables: VA interface, task and display condition. The two VA interfaces (ATL-Viz and RAD-Viz) were a between-participant variable. Participants answered 10 questions (i.e. tasks) for their respective interface and a control condition (i.e. traditional display system consisting of the

Table 2: *User tasks given in the questionnaire for understandability assessment.*

No.	Tasks	Task type
1	At which FL is the aircraft A and B predicted to lose separation?	Elementary lookup
2	Which aircraft in conflict is flying at the highest FL?	Elementary comparison direct (radial axis for ATL-Viz & angular axis for RAD-Viz)
3	Which aircraft in conflict is flying at the lowest FL?	Elementary comparison reverse (radial axis for ATL-Viz & angular axis for RAD-Viz)
4	What is the conflict geometry between these two aircrafts? (head-on)	Synoptic relation-seeking on glyph
5	What is the conflict geometry between these two aircrafts? (catch-up)	Synoptic relation-seeking on glyph
6	Which aircraft pair in conflict is the most imminent?	Elementary comparison direct (angular axis for ATL-Viz & radial axis for RAD-Viz)
7	Which aircraft pair in conflict is the least imminent?	Elementary comparison reverse (angular axis for ATL-Viz & radial axis for RAD-Viz)
8	Within the next *X* minutes, which aircraft will lose separation in-between FL Y and FL Z?	Synoptic pattern identification
9	Which aircraft in conflict has the largest rate of climb?	Synoptic behaviour comparison
10	Which aircraft requires the largest heading change in order to resolve the conflict?	Synoptic relation-seeking

Notes: FL: flight level.

radar screen and CARD). As such, these were within-participant variables. Thus, each participant answered each of the tasks twice (20 tasks in total): once for a sample traffic situation visualized on the control condition and once for the same traffic situation visualized on the VA interface tested (ATL-Viz or RAD-Viz).

In addition to resolving conflicts on the designed scenarios, a questionnaire was designed to evaluate the extent to which the display conditions affect participants effectiveness in understanding information about in-conflict pairs. Ten tasks were designed based on the task model presented in Andrienko and Andrienko [AA06]. Five elementary tasks were designed to evaluate performance in understanding information visualized on each axis of the polar graph separately. Further, synoptic tasks were designed to evaluate the extent to which the ATCo acquires a general insight about the whole traffic situation. Table 2 presents the 10 tasks. The tasks focussed on the information ATCos require to resolve conflicts efficiently. For example Q4 and Q5 concerned the information the ATCo needs to choose a suitable resolution strategy based on guidelines found in Great Britain, Civil Aviation Authority, Safety Regulation Group [GCS09]. Q6 and Q7 focussed on the information the ATCo needs to prioritize conflicts. Q8 examined the understanding of traffic density in occupied FLs. Q10 focussed on assessment of the heading resolution strategy, e.g. to choose a solution with the least deviation from the track.

4.4. Study 2: simulation

Study 2 evaluated the effects of the visualization concepts on ATCos' decision-making process in a simulation study. Participant interaction with conflict pairs and their subjectively experienced workload was measured.

Study 2 was a mixed-study design with three independent variables: visualization concept (two levels), display condition (two levels) and scenario complexity (two levels). The two visualization concepts ATL-Viz and RAD-Viz were varied between participants. The other variables were varied within participants (scenario complexity and display condition). In the display condition, participants used either the CARD display (control) or one of the visualization concepts (depending on the group).

Two traffic scenarios were used, one with low traffic complexity (scenario BS) and one with high traffic complexity (scenario CM). Complexity was increased by increasing the number of aircraft present in the scenario (traffic density in BS = 10 in CM = 17) that had no conflict with any other aircraft.

Conflict pairs and their geometries were designed based on Great Britain, Civil Aviation Authority, Safety Regulation Group [GCS09] guidelines, which are used to enhance ATCos emergency training programmes. To ensure that the designed traffic scenarios were realistic compared to daily traffic seen by ATCos, an ATCo with more than 14 years of experience as an approach controller was involved in the entire scenario design process. Conflict geometries and distances and initial velocities for conflicting aircraft were considered in the design of traffic scenarios, as previous research indicates that they may reduce the ATCos' accuracy of prediction. These parameters in the designed conflicts were all discussed with the expert ATCo. Five in-conflict pairs were designed and were the same across scenarios, A: a highly urgent climb-descent conflict with initial vertical distance of 11,000 ft and divergent conflict angle. B: an urgent climb-descent conflict with initial vertical distance of 20, 000 ft in catch-up configuration. C: a less-urgent cruise-descent conflict with initial vertical distance of 14, 000 ft and highly divergent conflict angle. D: a less urgent both-descending conflict in head-on configuration and E: a non-urgent both-cruising conflict in a catch-up configuration. Participants were asked to play the scenarios and resolve all conflicts.

To simplify, it was assumed that aircraft maintained constant speed during flight unless the controller ordered a change. Fluctuations in airspeed, wind effects and pilot intent were also excluded. Since all conditions contained the radar screen, to prevent participants from recognizing similar traffic patterns, each of the low and high traffic scenarios had been rotated 60, 120, 180 and 240° for the different display conditions. The assignment of rotation angle to the display conditions varied among participants. To avoid order-induced effects, a Fisher–Yates algorithm was used to randomly shuffle traffic scenario order for each participant. Note that the order of conflicts were not varied across scenarios: conflicts always appeared in the same order. The reason for this was to compare whether different ways of visualising temporal domain on VA interfaces affect ATCos' prioritisation in resolving conflicts (RQ3).

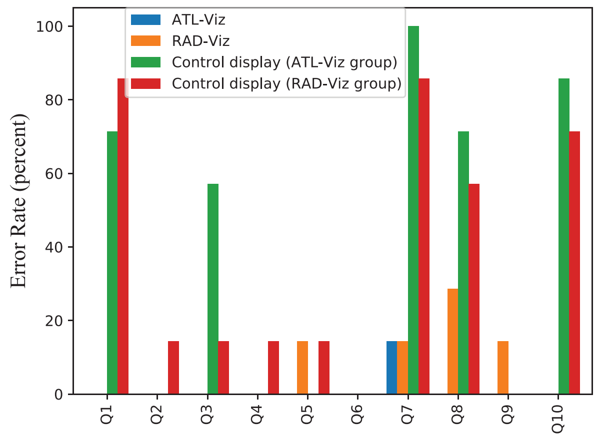

Figure 5: *Comparison between the control conditions, angular time line visualization (ATL-Viz) and radial time visualization (RAD-Viz) on error rate in information interpretation of traffic situations.*

4.5. Procedure

The experiment consisted of four steps. (A) Training session: a 20-min video was created in which the interfaces were introduced in details, with examples. Instructions about the study procedure were given to ATCos in the training video clip. The interactive features were also explained. (B) Familiarisation session: each participant worked with the control condition and either ATL-Viz or RAD-Viz. To make sure each participant had familiarized themselves with all features, a list of eight tasks were displayed at the top-right corner of the screen, inviting ATCos to explore interaction features and resolve conflicts by various strategies. Only one task was displayed at a time. A 'Done' button was placed next to the task description. When pressing the button, the next task was displayed. When all tasks were finished, the participant was asked to proceed to the next training scenario. In the familiarisation session, participants could click on additional buttons to get hints and learn about interactive features of the tool and the visualization concepts. These buttons were deactivated in step D. (C) Understandability assessment (Study 1). (D) Simulation (Study 2): the participants' task was to work with scenarios (low and high) on the VA interfaces and resolve the conflicts. At the end of each scenario, after pressing the 'Next' button, a message was presented, which asked the participant to rate the workload they experienced on a 1–100 scale.

Due to restrictions imposed on both participants and experimenters by the COVID-19 pandemic, the experiment was conducted entirely through a remote and offline protocol. Steps B–D of the experiment were implemented in Python by the first author and integrated into a single executable programme. The programme was sent to ATCos together with the training video. A digital consent form was shown upon starting the programme. In addition, each ATCo received a unique participant ID. The participant ID specified the order with which the scenarios of step D ran in the programme. ATCos were asked to run the study right after watching the tutorial video. The executive programme ran in full screen mode and could not be paused once started, to ensure that all participants were given an equal amount of time between familiarisation and running the experiment. The programme also prevented ATCos from moving to the next scenario without resolving all conflicts in the running part. The programme generated log file activities of all ATCos' interactions with the tool, and the participants sent those files to the first author via email, which was later analysed.

4.6. Data analysis

The data collected with ATCos were analysed descriptively. Considering the sample size and number of outliers in the data, non-parametric statistical methods were used. For understandability assessment (Study 1), a two-sided Wilcoxon signed-ranked test was used to compare the effects of the display conditions on task effectiveness within-participants (measured by task completion time and average error rate in percent). For the error rate, binary responses on correctness were analysed. For Study 2, because the number of conditions was four, Friedman's test was used to determine the effects of the display conditions on decision-making variables within-participants. To analyse display effects on dependent measures between-participants, a two-sided Mann–Whitney U test was used for both parts of the study. Only significant results are reported for an alpha of 0.05. Dunn–Bonferroni *post hoc* testing was conducted whenever a significant effect was observed. All *post hoc* tests were controlled for multiple comparisons. It should be noted that our analysis and conclusions from the experiment are based on a consideration of all results combined, not of results from a single statistical test.

5. Results

Results are presented in two parts: questionnaire results on the effectiveness in understanding the visualizations, and simulation results on the behaviour in user interactions and performance when resolving conflicts on the interfaces.

5.1. Study 1: effectiveness in understanding the information

Figures 5 and 6 depict a barplot for error rate values and a boxplot for response time for each of the 10 tasks in the questionnaire. When analysing within-participant differences, Figure 6 shows that ATCos answered tasks 1, 2, 3, 8 and 10 faster in the ATL-Viz condition than in the control condition. Task 6 stands out as ATCos in the

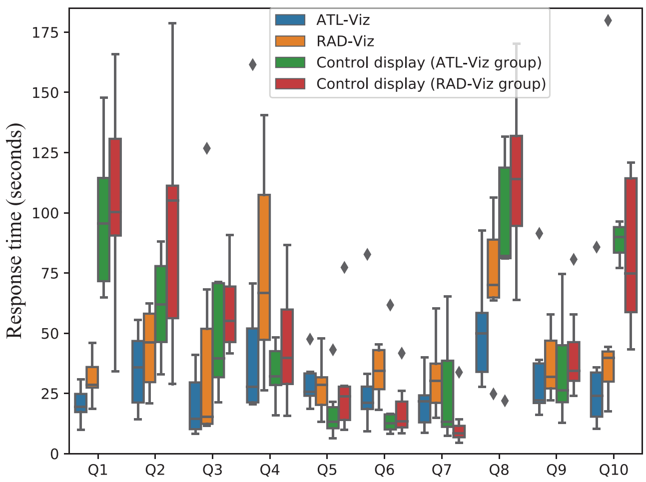

Figure 6: *Comparison between the control condition, angular time line visualization (ATL-Viz) and radial time visualization (RAD-Viz) on task completion time for the same traffic situation.*

ATL-Viz group answered this task faster in the control condition than in the ATL-Viz condition. ATCos answered task 1 faster in the RAD-Viz condition, while tasks 6 and 7 were answered faster in the control condition. The fact that ATCos answered tasks 1, 2, 3, and in particular 8 faster and more accurately on ATL-Viz than in other displays, indicates that ATL-Viz improved ATCos' vertical spatial understanding of traffic density patterns at occupied FLs.

Figure 5 shows that ATCos had more errors in the control condition for tasks 1, 3, 7, 8 and 10 than in the ATL-Viz condition. ATCos in the RAD-Viz group answered tasks 1, 7, 8 and 10 incorrectly more often in the control condition. Examining tasks, the results indicate that ATL-Viz helps ATCos understand, identify and compare information about where and when the conflicts will occur more effectively. Figure 6 suggests that ATCos could solve task 6 much faster using the control condition than in the VA conditions. Comparing ATCos' effectiveness in answering tasks 4 and 5 and considering the fact that no significant effect was observed for the display effects on error rate and response time, this suggests that ATCos can understand conflict geometries on glyphs just as well as on the radar screen. Based on Figure 6, tasks 2 and 9 were solved quicker on ATL-Viz than the other display conditions.

As depicted in Table 3, participants in the ATL-Viz group completed the questionnaire (10 tasks in total) significantly faster in the ATL-Viz condition than in the control condition. When considering number of errors across all tasks, the ATL-Viz group had significantly fewer errors in the ATL-Viz condition than in the control condition. For the RAD-Viz group, the Wilcoxon signed-rank test showed no significant effects between groups regarding task completion time. There was, however, a significant effect for number of errors, with fewer errors in the RAD-Viz condition compared to the control condition.

When analysing between-participant differences for the ATL-Viz and RAD-Viz groups, there were no significant differences for task completion times, or number of errors. However, considering time to answer individual tasks, ATCos solved task 1 faster in the ATL-Viz condition ($Mdn = 19.35,\ IQR = 8.79$) compared to the RAD-Viz condition ($Mdn = 28.49,\ IQR = 11.86$).

5.2. Study 2: simulation

Figure 7 depicts how the display conditions affected interaction with RAD-Vizin low- and high-complexity scenarios. The figure compares the time they started to interact with conflicts; the time they made a decision; which resolution type they used; the screen they chose to apply their strategy; the order followed to resolve conflicts and the time they hovered mouse over glyphs for individual conflicts. Each dot represents a click made on the screen or a mouse hover instance over the glyphs. Therefore, lines represent duration of mouse hover over the glyphs. Colours represent individual conflicts ranging from red to blue for the most imminent to the least imminent conflict. The sequence of events for each participant was separated with black horizontal lines. The figure shows that some participants had hovered the mouse over the glyphs then had momentarily clicked on another aircraft and then continued hovering the mouse over the initial aircraft. To increase salience on the reduced size plot shown here, interaction sequences with each conflict are separated with a small offset in y-axis for each participant.

5.2.1. *Number of clicks*

Our results show that, when working with the VA interfaces, fewer clicks were made on the radar screen, compared to the control condition. For the ATL-Viz group, a Friedman test showed a significant effect ($\chi^2(3) = 8.63,\ p = 0.035$) between the conditions.

Table 3: *Statistical results for participant performance in Study 1 (within participant).*

Measure	Statistics two-sided Wilcoxon sign-ranked test			
	ATL-Viz median (IQR)	ATL-Viz control median (IQR)	RAD-Viz median (IQR)	RAD-Viz control median (IQR)
Task completion time (s)	$Z = 2.197,\ p = 0.028$		$Z = 1.859,\ p = 0.063$	
	262.35 (243.19)	546.50 (207.43)	453.26 (175.06)	651.65 (268.27)
Number of errors	$Z = 2.414,\ p = 0.016$		$Z = -2.392,\ p = 0.017$	
	0 (0)	4 (2)	1 (1)	3 (2)

Notes: ATL-Viz: angular time line visualization; RAD-Viz: radial time visualization.

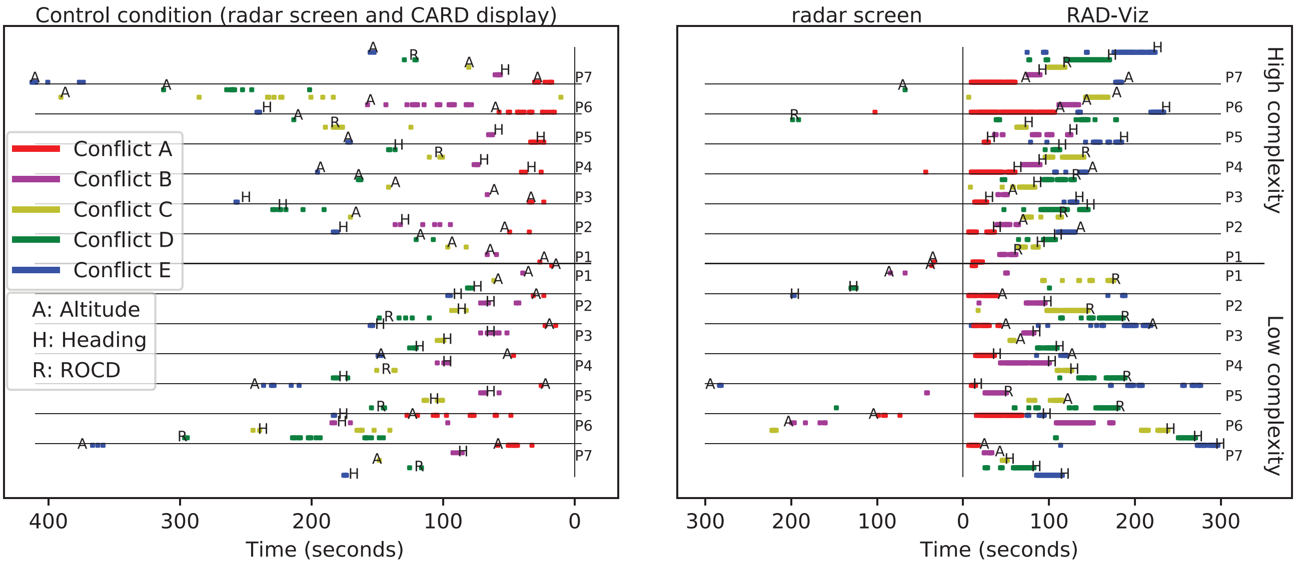

Figure 7: *Comparison of time to interact with conflicts between the two display conditions (RAD-Viz and the control condition) for both low- and high-complexity scenarios. Annotated text indicates the strategies ATCos followed to resolve conflicts.*

However, pair-wise *post hoc* tests showed that a significantly lower number of clicks were made on the ATL-Viz condition in high-complexity scenario than in the control condition in low-complexity scenario. For the RAD-Viz group, a significant effect was found between the display conditions ($\chi^2(3) = 16.25,\ p = 0.001$). *Post hoc* analysis revealed that, in the low-complexity scenario, significantly fewer interactions were made on the radar screen ($p = 0.025$) in the RAD-Vizcondition ($Mdn = 2,\ IQR = 7.5$) than in the control condition ($Mdn = 18,\ IQR = 2.75$). Likewise in a high-complexity condition, significantly fewer interactions with the radar screen ($p = .008$) were made in the RAD-Viz condition ($Mdn = 1,\ IQR = 1.75$) than in the control condition ($Mdn = 16,\ IQR = 10.75$).

5.2.2. *Display use for resolving conflicts*

Analysing the number of conflicts resolved on the radar screen in all display conditions, a Friedman test showed a significant effect for both the ATL-Viz ($p = 0.002$) and the RAD-Viz ($p = 0.000$) groups. Pairwise Dunn–Bonferroni follow-up tests performed on the ATL-Viz group showed that in the low-complexity scenario, a significantly ($p = 0.02$) lower number of conflicts were resolved on the radar screen in the ATL-Viz condition ($Mdn = 0,\ IQR = 4.25$) than in the control condition ($Mdn = 5,\ IQR = 0$). For the RAD-Viz group, in the high complexity scenario, a significantly ($p = 0.005$) lower number of conflicts were resolved on the radar screen in the RAD-Viz condition ($Mdn = 0,\ IQR = 1$) than in the control condition ($Mdn = 5,\ IQR = 0$).

Figure 7 shows ATCos hovered on the RAD-Viz (the colourful lines) before making a decision. This suggests that ATCos used the information about solution spaces offered on RAD-Viz in the decision-making process. Overall, the fact that the figure on the right is more colourful, busier and with shorter time gaps between consequent events than the figure on the left for the control display indicates that the design of the time–altitude display kept ATCos more engaged in interacting with the interfaces.

5.2.3. *Time to start interacting with conflicts*

Comparing the time it took for ATCos to start interacting with conflict pairs, as can be seen from the figure, for almost all ATCos, each colourful first click or mouse hover made in the RAD-Viz condition occurred earlier than in the control condition. When analysing the effect of display condition on time to start interacting with conflicts, in the ATL-Viz group a significant effect was found for conflicts A, B and D ($\chi^2(3)_A = 18.13,\ p_A < 0.000,\ \chi^2(3)_B = 8.22,\ p_B = 0.042,\ \chi^2(3)_D = 10.03,\ p_D = 0.018$). *Post hoc* tests showed that only conflict A was responded to significantly earlier in the ATL-Viz condition ($Mdn_{BS} = 5,\ IQR_{BS} = 7.5,\ Mdn_{CM} = 7,\ IQR_{CM} = 4.5$) than on the control display ($Mdn_{BS} = 18,\ IQR_{BS} = 15, Mdn_{CM} = 22,\ IQR_{CM} = 15$) in both low- ($p = 0.034$) and high- ($p = 0.014$) complexity scenarios. For the RAD-Viz group, the effect was significant for conflicts A, D and E ($\chi^2(3)_A = 14.34,\ p_A < 0.002,\ \chi^2(3)_D = 16.54,\ p_D = 0.001,\ \chi^2(3)_E = 12.77,\ p_E = 0.005$). *Post hoc* tests showed that in both low- and high-complexity scenarios, conflicts A ($p_{BS} = 0.01,\ p_{CM} = 0.04$) and E ($p_{BS} = 0.04,\ p_{CM} = 0.016$) were responded to significantly earlier in the RAD-Viz condition (BS: $Mdn_A = 7,\ IQR_A = 6.75,\ Mdn_E = 71,\ IQR_E = 91$; CM: $Mdn_A = 6,\ IQR_A = 3.5,\ Mdn_E = 103,\ IQR_E = 40.25$) than on the control display (BS: $Mdn_A = 22,\ IQR_A = 24,\ Mdn_E = 170,\ IQR_E = 54.5$; CM: $Mdn_A = 20,\ IQR_A = 7.25,\ Mdn_E = 192,\ IQR_E = 79.25$). Only in the high-complexity scenario was conflict D responded to significantly earlier ($p < 0.000$) in the RAD-Viz condition ($Mdn = 61,\ IQR = 28.25$) than on the control display ($Mdn = 159,\ IQR = 74.25$).

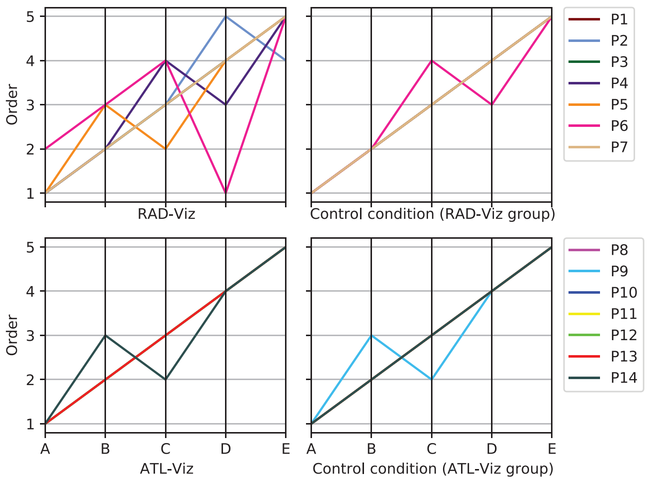

Figure 8: *Comparison between order of resolving conflicts in four display conditions in the high complexity traffic situation.*

5.2.4. *Order of resolving conflicts*

The order of resolving conflicts was compared between ATL-Viz and RAD-Viz (RQ3), by analysing descriptive graphs for all participants of both complexity scenarios. Figure 8 depicts display effects on the order of resolving conflicts in the complex scenario. The results indicate that ATL-Viz, in contrast to RAD-Viz, encourages ATCos to resolve conflicts based on urgency. Three out of four who did not resolve the conflicts in order of urgency in the RAD-Viz condition followed the urgency order in the control condition. However, when working with the control display, the participant who had only switched the order of resolving conflicts C and D (P6) had resolved all urgent-to-medium-term conflicts in an order not reflecting urgency when working with the RAD-Viz condition.

Comparing time to resolve conflicts, no significant effect was observed between the display conditions. The time to make decisions about conflicts was measured from the moment the previous conflict was resolved. The reason for this was that not all conflicts were resolved in the same order by ATCos, even though they mainly interacted with conflicts sequentially (in all conditions). Parallel interactions with several interaction pairs were rare (as depicted in the interaction diagrams). For the first conflict resolved, time was measured from the beginning of the scenario.

5.2.5. *Mouse hover duration*

Comparing mouse hover duration over glyphs between ATCos of the ATL-Viz and the RAD-Viz groups, no significant effect was found between the display conditions. However, analysing number of ROCD or heading resolution strategies made on the radar screen within participants, a significant effect was found between the display conditions for both groups (ATL-Viz: $\chi^2(3) = 13.63,\ p = 0.003$ and RAD-Viz: $\chi^2(3) = 13.95,\ p = 0.003$). For the ATL-Viz group, follow-up tests showed that in the high-complexity scenario significantly fewer ($p = 0.02$) ROCD or heading resolutions were applied on the radar screen when working with ATL-Viz ($Mdn = 0,\ IQR = 1$) compared to the control display ($Mdn = 4,\ IQR = 1.75$). For the RAD-Viz group however, in the low-complexity scenario, a significantly lower ($p = 0.005$) number of ROCD or heading resolutions were applied on the radar screen when working with RAD-Viz ($Mdn = 0,\ IQR = 0$), compared to the control display ($Mdn = 3,\ IQR = 0.75$).

5.2.6. *Resolution strategies and workload*

No significant effect was found between the display conditions, neither for resolution strategies nor for self-rating workload values. Results for statistical tests performed on decision-making measures compared between participants of ATL-Viz and RAD-Viz showed no significant effect of the display conditions—neither between the RAD-Viz and the ATL-Viz condition nor between the control conditions (see Table 4 in Appendix 2).

5.2.7. *ATCos' qualitative feedback*

Six of the 14 ATCos also provided written qualitative feedback on their experience with the interfaces when submitting their files for analysis. Visualization of solution spaces was described as 'important and helpful' for them. However, two en-route ATCos found it challenging to get used to the polar graph visualization after working with CARD display for many years. Approach controllers from the RAD-Viz group found representation of urgency on RAD-Viz non-intuitive. The fact that outer circles meant shorter time to conflict while inner ones referred to longer remaining time did not feel natural for them. As stated by one ATCo: 'naturally, our perception is that a longer line means you have more time to react. But for this interface, it is the opposite'.

6. Discussion

The initial known issue of current conflict detection tools is the low level of what-if probe functionalities, which results in high workload for tactical controllers. Enhanced conflict management tools are expected to assist ATCos in conflict resolution by indicating available and occupied FLs and allowing the user to probe for conflicts on a what-if trajectory. This was the main motivation behind the development of the two VA decision-support tools ATL-Viz and RAD-Viz, that allow ATCos to visually analyse conflict situations in real time. The interfaces were designed, implemented in Python, and evaluated with domain experts. The design contribution is unique in two aspects. First, in line with generally preferred resolution strategies (e.g. [AMVP06, WAS99]), the focus is on visualising information that provides vertical solution space criteria. As a result, the proposed VA interfaces are expected to support ATCos' cognitive effort to develop a mental picture of the vertical relationship between aircraft in conflicting situations, and to enable what-if and what-else FL probe functionalities for them. This entails addressing the cognitive task limitation of the currently used radar screens and CARD displays. Second, applying a glyph-based visualization technique, the designed VA interfaces enable ATCos to visualize and compare all possible solution spaces for all conflicts simultaneously. The motivation for glyph-based visualization was shaped by qualitative feedback received from ATCos in the study of Zohrevandi *et al.* [ZWLY20]. ATCos found the TA display more useful (than the radar screen and CARD) for detecting urgent conflicts consisting of a mixed climb-descent aircraft pair. This conflict type is a highly severe incident in ATC, and preventing it is among the EUROCONTROL top-five operational safety priorities [BLCS14]. The glyph-based visualization of our VA interfaces enables the ATCo to closely examine safe rate of climb and descent solution spaces, especially during highly urgent situations. Below, we discuss how the main findings of the study address our research questions.

1. *Identifying the effects of the designed VA interfaces on ATCos' understanding of the information*: our findings showed that ATCos understood the information about conflicts more quickly and more accurately when provided with the ATL-Viz visualization. When using both ATL-Viz and RAD-Viz, ATCos' effectiveness in understanding the information outperformed the baseline system (radar screen + CARD display) in a variety of tasks, including lookup, comparison in reverse direction, pattern identification and relation seeking. Moreover, on ATL-Viz, ATCos could look up the FL at which aircraft pairs will lose separation more quickly than when working with RAD-Viz and currently used displays. Thus, we first conclude that **a holistic visualization of altitude solution spaces improves ATCos' effectiveness in understanding aircraft conflict situations**. Moreover, we conclude that **mapping altitude-based information and time over the radial and angular axis of the polar graph (as visualized on ATL-Viz)** improved effectiveness of understanding the information about altitude solution spaces. Second, since all ATCos of the ATL-Viz group performed tasks 4 and 5 in Study 1 correctly, **we conclude that the composite glyph conveyed the encoded information correctly**. This finding indicates that they understood the conflict geometries correctly. We further **conclude that the novel design of composite glyph presented in this work was useful for ATCos in resolving conflicts**. The conclusion is based on the finding that significantly fewer ROCD and heading resolution strategies were made on the radar screen in the VA interface conditions than in the control condition.
2. *Identifying the effects of the designed VA interfaces on ATCos' decision-making process*: the results showed that VA interfaces improved interaction and decision-making process for ATCos in terms of how early they started to interact with conflicts. Based on the results, we conclude that ATCos' time to start interacting with the most urgent conflict on both VA interfaces outperformed the control condition. Regarding resolution strategies, perceived workload and actual time to resolve conflicts, the results did not show any significant impact. We can thus conclude that the new VA interfaces did not add additional workload or increased time to resolve conflicts.
3. *Investigating whether various ways of mapping time and FL information on the polar graph axes affect ATCos' performance in prioritising conflicts*: we conclude that the **metaphoric visualization of time–altitude display in ATL-Viz(mapping temporal domain to angular axis implying clock metaphor) does affect task prioritisation for ATCos**. This is supported by two findings. First, on ATL-Viz conflicts were resolved in the order of urgency. Second, we did not find this effect with RAD-Viz.

There was some uncertainty in measuring glyph effectiveness in our experiment. Hovering over the glyph could be a result of confusion or not paying attention, i.e. hovering but looking at something else. However, based on study results depicted in Figure 5, all 14 ATCos (except for one ATCo from the RAD-Viz group) answered tasks about conflict geometry correctly (Q4 and Q5). Second, statistical results showed that there was no significant effect of the display conditions on the time needed to resolve conflicts. This means that hovering the mouse over glyphs did not take extra decision-making time from ATCos. Third, significantly more rate of climb or heading resolution strategies were made on the glyphs than on the radar screen. This indicates that hovering the mouse over glyphs resulted in successful decision-making, which supports the notion that the glyphs were used. Such claims could be further assessed if we could analyze eye movement patterns using eye tracking.

Conducting this study during the COVID-19 pandemic was challenging. Considerable work was dedicated to integrating the whole experiment setup in a stand-alone executable file, which could run on any computer, to reach participants who were for instance working from home. Another downside was that we had less control of what participants did when conducting the experiment and it was not possible to observe their interaction. However, the upside was that it enabled us to conduct the study with expert ATCos from different countries. This led to having more participants, which is an opportunity to consider in future experiments.

7. Conclusion and design guidelines

To conclude, the polar graph technique used in ATL-Viz and the focus + context visualization of solution spaces used in the composite glyph significantly improved ATCos' ability to understand conflicting situations compared to a control condition representing currently used ATC displays. This is highly relevant considering that participants are used to the traditional CARD and radar displays that visualize conflict geometries on the *x–y* plane. Drawn from the results, we recommend the following three design guidelines.

First, **using the clock metaphor benefits task prioritisation**. The utility of the approach is shown by the finding that visualization of temporal patterns on the polar graph angular axis (as visualized on ATL-Viz) supports operators in prioritising and resolving conflicts based on urgency.

Second, **the polar graph technique supports organisation of time and highlights one solution space dimension**. Altitude-based solutions were highlighted and used in our studies. ATCos could thus visualize and compare, in real time, altitude-based solutions without having the need to hover the mouse over glyphs. The finding that on both VA interfaces ATCos' effectiveness in understanding vertical relationship between conflicts outperformed the control condition, suggests that highlighting ATCos' preferred resolution strategy improves their understanding of such information.

Third, **the composite glyph technique aids in integration and real-time comparison of multi-dimensional information about solution spaces**. The study results indicated that the technique was successful in focus + context visualization of multidimensional information about solution spaces. Thus, when there is a need for visualization and real-time comparison of time-critical information on solution spaces (horizontal and vertical solution space, what-if and what-else probe functionalities), using the composite glyph is beneficial.

Finally, our investigations indicate that application of ATL-Viz to other application domains where complex real-time decision-making is important (e.g. traffic monitoring for sea, rail and emergency response) could improve time critical workflows.

References

[AA06] Andrienko N., Andrienko G.: *Exploratory Analysis of Spatial and Temporal Aata: A Systematic Approach*. Springer Science & Business Media, Berlin, Heidelberg, 2006. https://doi.org/10.1007/3-540-31190-4.

[ACS18] Ayhan S., Costas P., Samet H.: Prescriptive analytics system for long-range aircraft conflict detection and resolution. In *Proceedings of the 26th ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems* (2018), pp. 239–248. https://doi.org/10.1145/3274895.3274947.

[ALP12] Albrecht G., Lee H.-T., Pang A.: Visual analysis of air traffic data using aircraft density and conflict probability. American Institute of Aeronautics and Astronautics (2012). https://doi.org/10.2514/6.2012-2540.

[AMVP06] Appleton R., Mulder M., Van Paassen R.: Comparison of two interfaces for supporting pilots in airborne self-separation tasks. In *Proceedings of the AIAA Guidance, Navigation, and Control Conference and Exhibit* (2006). https://doi.org/10.2514/6.2006-6062.

[BBE*15] Beernink B., Borst C., Ellerbroek J., van Paassen R., Mulder M.: Toward an integrated ecological plan view display for air traffic controllers. In *Proceedings of the 18th International Symposium on Aviation Psychology* (2015), pp. 55. https://corescholar.libraries.wright.edu/isap_2015/98.

[BBVPM17] Borst C., Bijsterbosch V. A., Van Paassen M., Mulder M.: Ecological interface design: supporting fault diagnosis of automated advice in a supervisory air traffic control task. *Cognition, Technology & Work 19*, 4 (2017), 545–560.

[BJA*15] Buchmüller J., Janetzko H., Andrienko G., Andrienko N., Fuchs G., Keim D. A.: Visual analytics for exploring local impact of air traffic. *Computer Graphics Forum 34*, 3 (2015), 181–190.

[BKC*13] Borgo R., Kehrer J., Chung D. H. S., Maguire E., Laramee R. S., Hauser H., Ward M., Chen M.: Glyph-based visualization: foundations, design guidelines, techniques and applications. In *Proceedings of the Eurographics 2013 – State of the Art Reports*. M. Sbert and L. Szirmay-Kalos (Eds.). The Eurographics Association (2013). https://doi.org/10.2312/conf/EG2013/stars/039-063.

[BLCS14] Blajev T., Licu A., Cooper N., Sultana J.: Operational Safety Study: Blind Spots, Inefficient Conflict Detection with Closest Aircraft. Technical report, EUROCONTROL, 2014. https://www.eurocontrol.int/publication/blind-spots.

[BRA16] Bole-Richard D., Abert A.: Separation Task in En-Route Trajectory-based Environment. Technical report P04-07-02, SESAR, 2016.

[BTD14] Buschmann S., Trapp M., Döllner J.: Real-time animated visualization of massive air-traffic trajectories. In *Proceedings of the 2014 International Conference on Cyberworlds* (2014), pp. 174–181. https://doi.org/10.1109/CW.2014.32.

[Dur04] Durlach P. J.: Change blindness and its implications for complex monitoring and control systems design and operator training. *Human–Computer Interaction 19*, 4 (2004), 423–451.

[FFM12] Fischer F., Fuchs J., Mansmann F.: ClockMap: enhancing circular treemaps with temporal glyphs for time-series data. In *Proceedings of the EuroVis – Short Papers*. M. Meyer and T. Weinkaufs (Eds.). The Eurographics Association (2012). https://doi.org/10.2312/PE/EuroVisShort/EuroVisShort2012/097-101.

[FFM*13] Fuchs J., Fischer F., Mansmann F., Bertini E., Isenberg P.: Evaluation of alternative glyph designs for time series data in a small multiple setting. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (New York, USA, 2013), ACM Press, pp. 3237–3246. https://doi.org/10.1145/2470654.2466443.

[GCS09] Great Britain, Civil Aviation Authority, Safety Regulation Group: *Radar Control: Collision Avoidance Concepts*. TSO, 2009. OCLC: 503260608. URL: https://publicapps.caa.co.uk/docs/33/CAP717.PDF.

[HCGT14] Hurter C., Conversy S., Gianazza D., Telea A.: Interactive image-based information visualization for aircraft trajectory analysis. *Transportation Research Part C: Emerging Technologies 47* (2014), 207–227.

[Hil04] Hilburn B.: Cognitive Complexity in Air Traffic Control: A Literature Review. EEC note 4, 04, 2004, pp. 1–80. https://www.eurocontrol.int/node/9861.

[HTC09] Hurter C., Tissoires B., Conversy S.: Fromdady: Spreading aircraft trajectories across views to support iterative queries. *IEEE Transactions on Visualization and Computer Graphics 15*, 6 (2009), 1017–1024.

[Joh02] Johnson W. W.: Effects of symbol brightness cueing on attention during a visual search of a cockpit display of traffic information. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting 46*, 17 (2002), 1599–1603.

[KFM11] Kintzel C., Fuchs J., Mansmann F.: Monitoring large ip spaces with clockview. In *Proceedings of the 8th International Symposium on Visualization for Cyber Security* (New York, USA, 2011), ACM Press, pp. 1–10. https://doi.org/10.1145/2016904.2016906.

[KVDZT14] Klein T., Van Der Zwan M., Telea A.: Dynamic multiscale visualization of flight data. In *Proceedings of the 2014 International Conference on Computer Vision Theory and Applications (VISAPP)* (2014), vol. 1, IEEE, pp. 104–114. https://ieeexplore.ieee.org/document/7294794.

[LCVPM11] Lodder J., Comans J., Van Paassen M., Mulder M.: Altitude-extended solution space diagram for air traffic controllers. In *Proceedings of the 16th International*

Symposium on Aviation Psychology (2011), pp. 345. https://corescholar.libraries.wright.edu/isap_2011/57.

[LSJ*15] LUNDBERG J., SVENSSON Å., JOHANSSON J., JOSEFSSON B., SCHAEFER D.: Human-automation collaboration strategies. In *Proceedings of the Fifth SESAR Innovation Days* (2015). https://www.sesarju.eu/sites/default/files/documents/sid/2015/SIDs_2015_paper_20.pdf.

[MTH*16] MARCOS R., TORIBIO D., HERRANZ R., GARRIGÓ L., ALSINA N., ADRIENKO N., PIOVANO L.: Visual analytics and machine learning for air traffic management performance modelling. In *Proceedings of the Sixth SESAR Innovation Days* (2016). https://www.sesarju.eu/sites/default/files/documents/sid/2016/SIDs_2016_paper_36.pdf.

[MVMVP10] MERCADO-VELASCO G., MULDER M., VAN PAASSEN M.: Analysis of air traffic controller workload reduction based on the solution space for the merging task. In *Proceedings of the AIAA Guidance, Navigation, and Control Conference* (2010). https://doi.org/10.2514/6.2010-7541.

[R*92] REDDING R. E., et al.: Cognitive Task Analysis of Prioritization in Air Traffic Control. Technical report ED340849, Human Technology, Inc., McLean, VA, Jan. 1992. http://eric.ed.gov/?id=ED340849.

[RLMJ05] ROSENHOLTZ R., LI Y., MANSFIELD J., JIN Z.: Feature congestion: a measure of display clutter. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (New York, NY, USA, 2005), Association for Computing Machinery, pp. 761–770. https://doi.org/10.1145/1054972.1055078.

[RN05] RANTANEN E., NUNES A.: Hierarchical conflict detection in air traffic control. *International Journal of Aviation Psychology 15* (Oct. 2005), 339–362.

[VDMVP08] VAN DAM S. B., MULDER M., VAN PAASSEN M.: Ecological interface design of a tactical airborne separation assistance tool. *IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans 38*, 6 (2008), 1221–1233.

[War08] WARD M. O.: *Multivariate Data Glyphs: Principles and Practice*. Springer, Berlin, Heidelberg, 2008, pp. 179–198. https://doi.org/10.1007/978-3-540-33037-0_8.

[WAS99] WILLEMS B., ALLEN R. C., STEIN E. S.: Air Traffic Control Specialist Visual Scanning II: Task Load, Visual Noise, and Intrusions into Controlled Airspace. Technical report DOT/FAA/CT-TN99/23, Federal Aviation Administration, William J. Hughes Technical Center, 1999. https://doi.org/10.1037/e444742005-001.

[Xin07] XING J.: Information complexity in air traffic control displays. In *Human-Computer Interaction. HCI Applications and Services*. J. A. Jacko (Ed.). Springer, Berlin, Heidelberg, (2007), pp. 797–806. https://doi.org/10.1007/978-3-540-73111-5_89.

[ZWLY20] ZOHREVANDI E., WESTIN C. A. L., LUNDBERG J., YNNERMAN A.: Design of a real time visual analytics support tool for conflict detection and resolution in air traffic control. In *Proceedings of the EuroVis 2020 – Short Papers*. A. Kerren, C. Garth, G. E. Marai (Eds.) The Eurographics Association (2020), pp. 31–35. https://doi.org/10.2312/evs.20201044.

Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Data S1

Figure 1: Left: A climb-descent conflict as shown on HTA-Viz.

Figure 2: Left: A traffic scenario shown to the ATCos on HTA-Viz with three urgent climb-descent conflict pairs close to the loss-of-separation line.

Table 1: Statistical results for two-sided Wilcoxon sign-ranked test performed on understandability assessment measures compared within participants

Table 2: Statistical results for two-sided Mann-Whitney U test performed on understandability assessment measures compared between participants

Table 3: Results for statistical tests performed on decision-making measures compared within participants of each VA group tested

Table 4: Results for statistical tests performed on decision-making measures compared between participants of ATL-Viz and RAD-Viz groups

Figure 3: Comparison on time to interact with conflicts between ATL-Viz and the control condition for both low- and high-complexity scenarios. The annotated text indicates the strategies ATCOs followed to resolve conflicts