Mapping the Decision-Making Process of Conflict Detection and Resolution in En-Route Control: An Eye-tracking based approach

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***Abstract*—The objective of en-route control is to ensure minimum separation between aircraft in the sector under all circumstances. Exploring and understanding the related work patterns of air traffic controllers on how to successfully perform this task is crucial for the future development and implementation of automation solutions. Future automation must match the logic of decision making and the need for information at the right time in identifying and resolving conflicts. The objective of this paper is to identify "decision cues" that are relevant during decision-making and its relation to the controller's intention. A retrospective think aloud method was applied in which en-route controllers commented their own work behaviour after playing a simple conflict scenario in the simulator. A set of decision cues were identified using 13 controllers and classified using a Conflict Life Cycle-model, dividing the task into four work steps. The result shows clear differences in the compilation of decision cues used between work steps. Large differences were found among controllers, indicating personal preferences in consideration of information, timing, and chosen conflict resolution. The results further show that the "conflict resolution probing" step is the most challenging task because it contains the most decision cues. The high inter-individual variance in the cue composition of this step indicates a high degree of individual skill development on which the adoption and selection of conflict solutions is based. The results support the future hypothesis-driven verification of controllers' work pattern and intention of decision-making and related automated solutions.**

***Keywords*—Human Performance, Visual Scan Pattern, Eye-Tracking, Enroute Control, Air Traffic Control, Conflict Detection and Resolution**

I. INTRODUCTION

En-route control has the objective to assure a safe and expeditious flow of air traffic movements in controlled airspace. The central task of the air traffic controller (ATCO) working in this environment is conflict detection and resolution (CD&R). As part of the future implementation of automation, air traffic controller (ATCO) training, and workload self-assessment, system designers and safety decision-makers are calling for a better understanding of the work methods ATCOs apply to build situation awareness and how changing work characteristics might affect them. We define a work pattern as a temporally distributed sequence of observable and measurable activities, including information gathering (information cues), timing, and other decision cues, for decision making [1], [2]. In the specific context of en-route control, visual information gathering, in addition to radio communication, is mainly done by systematically scanning the field of view to gather information and build situational awareness, which in turn is used for decision-making. ATCOs thus apply visual scanning patterns that follow trained work patterns for performing their working tasks safely [1], [3].

Any innovation-driven change may raise safety concerns, as the work patterns used could change and become inappropriate if not adequately trained and adapted to the changing work characteristics. Observing and measuring, and when possible quantifying, any change in ATCO work pattern supports change management by better matching innovation with prevailing work pattern. Inadequately adapted innovations may, in turn, impact situation awareness and evoke safety risks that are to be identified and assessed earlier in the life cycle.

An important prerequisite for predicting the effects of changing work characteristics on the work pattern and related decision-making is to determine the information cues required, the appropriate timing, and other decision factors (information, timing and others relevant for decision-making, or briefly decision cue) that may be affected by the change [1]–[3]. There is little support for system designers and safety assessors in predicting the effects of change on work pattern, and considering them analytically. This relates in particular to the use of decision cues that must be appropriate to the intent of the situation at hand and build situational awareness on the right cue at the right time. This timing aspect is of particular importance, as the resolution of conflict situations requires a step-by-step approach, as shown by Pawlak [4].

There is a need to improve the ability to disclose work pat-

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terns and underlying decision-making processes. This relates primarily to the ability to make knowledge and skills used by ATCOs explicitly available. A challenging circumstance in identifying temporal-distributed cues in decision-making might be the use of methods in the domain of cognitive work analysis, such as the Hierarchical Task Analysis or the novel “Joint Cognitive Framework”, based on Hollnagels “Joint Cognitive Systems” [5]. They typically rely on workshop, interviews or/and experimental data. However, a major limitation of many workshop and interview approaches is that ATCOs’ work patterns are implicit and unconscious knowledge. Implicit knowledge about work skills are difficult to document (tacit knowledge [6], [7]) or to analytically annotate. This leads to the paradoxical circumstance that ATCOs have limitations in being able to disclose their own work pattern, even though they apply it perfectly in every day shift at work. Experimentally/empirically collected data, on the other hand, underlies limitations due to missing context, providing observational data that is non-interpreted and not linked to any intention of the ATCO. A bunch of observational data on its own, e.g. video or eye tracking, gives no clue if a change is of relevance in regards of the situation awareness obtained. Concerning experimental data, this includes the ability to contextualize observational data by giving the ATCO’s associated intent to the situation at hand.

One solution could be a combination of both sides using the Retrospective Think Aloud (RTA) method as described by [8]. The advantage of RTA is that the playback of a reference scenario harmonizes the situation to which an ATCO refers across all participants, rather than simply freely choosing a situation that a particular ATCO assumes. This makes ATCO statements more comparable and inter-individual variances in the work pattern more visible. Combining post-simulation interviews of en-route controllers and eye-tracking was already investigated by Palma Fraga [9], showing elementary information cues of conflict resolution (Altitude, Direction, Speed, Position, Destination, etc.) and geometric scan pattern.

As part of a proof-of-concept study, this paper presents the results of an exploratory eye tracking-stimulated RTA interview study aimed at analyzing ATCOs’ work pattern during CD&R. The self-assessment is supported by presenting ATCOs an eye-tracking playback of their own work pattern from a human-in-the-loop simulation they performed immediately prior.

The first objective of this study is to identify information, timing and other cues (decision cues) that are of relevance for the en-route ATCO’s decision-making, shaping and explaining the resulting work pattern observed during a simulated conflict situation. Decision cues are identified to develop hypotheses that provide the bases of a hypothesis-driven verification using eye-tracking only at a later subsequent study. The second objective is to relate decision cues to the work steps of the CD&R-task, the related purpose, and the intention of the ATCO. In this way, we support future innovation by showing how the step-wise approach to CD&R tasks corresponds to a sequence of intentions, associated decision cues, and resulting observable work patterns. Therefore, we focused on the variety of cues used by ATCOs and how they relate to a specific intent and purpose. This includes not only visual cues, but also the temporal aspect of their relevance during decision making, as suggested by Pawlak [4].

The paper first describes the approach used to generate the eye-tracking playbacks used for interviews, including the planning and conduction of human-in-the-loop simulations. The ATCOs’ collected statements of decision cues are then presented in a structured form that corresponds to the working pattern used in CD&R. In determining an appropriate structure, we will seek and consider indications of the work steps the ATCO must take from detection to successful resolution. Results are discussed with respect to the decision cues identified, their diversity and variances within as well as between ATCOs and work steps of CD&R.

II. RELATED WORK

In CD&R, the most important working instruments are radar, planning and conflict detection tools that support early detection solution generation by providing a traffic situation picture to the ATCO. Automation aid supports the ATCO, using tools such as speed vectors and “separation tools” (e.g., septool in the Thales TopSky-System), to achieve the level of situational awareness required to make effective and safe decisions. Over the years, several human information processing theories have been proposed for describing the work of an ATCO, including the CD&R task [4], [10]–[12].

Pawlak et al. [4] proposed a cognitive task model describing an ATCO’s perceived complexity of a traffic situation in relation to the primary task of traffic separation. The model forms a continuous processing cycle consisting of planning, implementation, monitoring, and evaluation. In this view, the CD&R task appears straightforward: On the basis of the perceived and forecasted traffic patterns, it detects potential conflicts and develops a plan for how to address them. A conflict between aircraft(s) exist when two or more aircraft are predicted to pass one another within a defined separation criteria, e.g. within 5nm horizontally and 1000ft vertically in Reduced Vertical Separation Minima (RVSM) airspace. To execute this plan, the ATCO identifies required interventions and implements them. The actions are monitored to ensure that the situation develops according with the plan. Finally, the effectiveness of the plan for solving the situation is evaluated, which leads to revised or new plans. In this model, the implemented physical actions (i.e. communication, data entry) are the only externally observable actions in the CD&R cognitive task cycle. However, the use of eye tracking equipment allows for also observing the other cognitive processes.

Cognitive CD&R task models generally argue that ATCOs search and probe for conflicts following a hierarchical structure. The process involves determining vertical separation by acquiring information on aircraft altitude/flight level, lateral separation by means of trajectory extrapolation (with support from support tools, and longitudinal separation by estimating the speed-distance relationship [13]–[16]. In doing so, different strategies are used, such as searching for contraction rates rather than expansion, cognitive motion extrapolation, and constant bearing comparisons [17].

Research on naturalistic decision making argues that experts typically do not identify and weigh several options. Rather, the action taken reflects the first credible option conceived intuitively through a process of pattern-recognition using tacit knowledge that builds on experience [7]. A solution that has previously worked well, is likely to be applied again in a similar situation.

ATCOs CD&R strategies have also been considered, by Borst et al. [18], in the context of investigating the training effect of using ecological interfaces based on a Solution Space Diagram (SDD). Based on a simulation study with en-route conflict scenarios performed by novice controllers, Borst et al. concluded that there was no difference between the group using the SDD interface and the group being instructed. In contrast to the work presented in [18], the objective of our work is to identify "decision cues" that are relevant for the underlying CD&R decision process.

A. *Eye tracking in ATC*

Palma Fraga's paper reports three types of results [9]:

- visual search patterns used by the ATCOs
- cues (aircraft information: altitude, direction, and speed)
- how the conflicts were solved (altitude change, etc)

Previous research in ATC attest to the importance of visual scanning for developing and maintaining situation awareness, detecting conflicts, and solving them. A majority of this research has, however, been limited to traffic monitoring and conflict detection. Using eye tracking technology, McClung and Kang [19] studied ATCOs eye movements of radar displays en-route ATC to identify visual scanning strategies for implementation in training programs. Eye tracking data was collected from 24 ATCOs in scenarios with traffic levels varying between 12 to 20 aircraft. Circular scanning patterns, followed by linear patterns, were found to be most dominant when scanning the radar display to search and solve conflicts.

Westin et al. [3] used eye tracking equipment to study tower ATCOs' eye movements in tower control with the objective to identify standardized 'best practice' visual scan patterns during approaches. Gaze overlaid video replays of ATCO's eye tracking recordings were used as a stimuli in a workshop with three tower ATCO instructors. Following an interview protocol around the stimuli, the researcher triggered discussions on visual information cues and scan patterns in relation to sub-tasks of an aircraft on approach scenario. The instructors were asked to answer and annotate information cues and scan patterns on printed images of the working environment. Questions included " *what were the critical visual checks in this approach?*" and "*Where should the ATCO look, and is there a specific order in which information is looked at?*" [3, p.3] Following the workshop, the authors explored the existence of identified scan patterns in eye tracking recordings using the visual sequence mining tool ELOQUENCE (ExpLOratory seQUENCE mining) [20]. The workshop identified six visual scan patterns, of which the following four were verified using ELOQUENCE in eye tracking recordings: runway scans, landing clearance, touchdown and landing roll, and phases of visual focus.

Meyer et al. used [1] a verbal coding technique (concurrent think aloud, CTA) that ATCOs applied during an eye-tracking field study in the tower of Linköping City Airport.

Lundberg et al. analyzed in 2014 [21] ATCO tool usage in an eye tracking study during a competence assurance exercise. It indicated that there might be a trade-off between using an own independent traffic scan and use of a specific tool (MTCD) to identify conflicts. The study also showed that during this exercise, ATCOs spend their main attention on the main situation display, rather than on side-screens.

III. METHOD

We conducted semi-structured, post-simulation/debriefing, interviews where ATCOs were asked to describe how they worked to detect and resolve conflicts. The semi-structured approach was chosen because of openly gather cues that the ATCO considers as relevant. For this, they were supported by eye-tracking video playback of their own recording from the simulation prior to the interview with eye gaze marking indicating their scanpath. The resulting decision cues are allocated to the respective purpose and intention of the ATCO. For the work steps applied by the ATCO and the related intention of the steps, we adapted the framework, proposed by Pawlak [4], to our Conflict Life Cycle (CLC), as shown in Figure 1 by the grey areas. The CLC divides the CD&R task into the following work steps:

1) **Conflict Detection** - The ATCO searches for conflict pairs that may show the potential to undermining minimum separation.
2) **Conflict Solution Probing** - The ATCO evaluates the situation and considers different scenario and actions for resolving the conflict while keeping disruption to flight deck crew and air traffic flow to a minimum
3) **Solution Implementation** - The ATCO implements the selected scenario as the preferred solution to the current conflict, finding a trade-off between the time required to evaluate possible scenarios and efficiency as described by the Efficiency-Thoroughness Trade-Off [22].
4) **Solution Monitoring** - The ATCO periodically checks the progress of the predicted separation distance at the closest point of approach (CPA) and whether the selected solution turns out as planned. When both aircraft pass the CPA, the conflict life cycle ends.

The statements of the ATCOs are then classified by matching the verbal statements against the steps of the CLC.

A. *Participants*

The human-in-the-loop simulations were conducted using ATCOs with valid rating for enroute control. In total, thirteen (four women) Swedish ATCOs from the Air Traffic Control

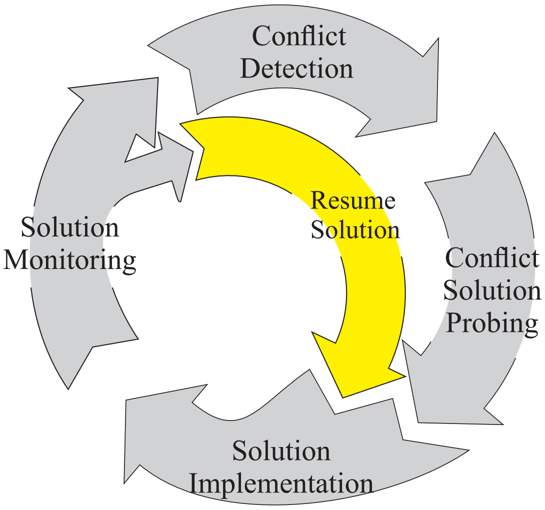

Figure 1. Conflict Life Cycle

Center Malmö (mean age 43.1 years and mean operational experience 16.9 years) completed the simulation and debriefing.

B. Simulator and Eye Tracking System

An en-route ATC simulator was used that bases on the NARSIM simulation platform, including a working position for the executive ATCO (EC) and two center pilot working positions. The primary working instrument involved a radar visualization of the respective sector, showing the sector borders, waypoints and the movements among others. The interface provided support tools in terms of speed vectors, a “sep tool” and a CD&R window. Figure 2 shows the radar screen with an example visualization of the eye-tracking measured scanpath, connecting several fixation via a blue arrow. The eye-tracking video playback for the ATCO interviews shows a similar visualization, just showing one fixation marker at a time and no arrow. The figure also shows two conflicting aircraft marked with the sep tool, indicated by the vectors (dark-red) showing the predicted separation distance of the respective aircraft at the point of closest approach.

The SmartEye eye-tracking system was used to capture and record participants visual activity. The equipment recorded eye gaze movements at a sampling frequency of 60 Hz and calculated the screen coordinates from this. The contents of the radar screen were recorded as a video file and overlaid with the eye gaze marker. The result was a video recording showing the radar screen content and the scanpath of the ATCOs during the simulation. The movement of the eye gaze marker is smoothed with a low-pass filter to avoid disturbances due to high-frequency noise. A python script was made to extract the eye gaze point visualized as a red gaze circle, from the eye tracking data, combined with the frame grabbed video.

C. Scenarios & Experimental Design

In this paper, we focus exclusively on one simple, generic, conflict scenario. This scenario was chosen for the playback due to its short length and lower level of complexity (approximately 8 min). Being part of a larger study, the conflict scenario was one of six conflict scenarios.

The scenario contained four aircraft: an Airbus 320, Boeing 737, and two Boeing 777. The scenario is shown in Figure 2. The sector was squared, 55x55 nm in size. The medium sized Boeing 737 and heavy sized Boeing 777 were in conflict as their flight-plans crossed at the same level (FL360) at 90 degrees angle. The other aircraft, on contradictory courses with the ones in conflict, acted as constraints to solving the conflict. The other Boeing 777 was crossing the sector 1000ft below the aircraft in conflict, at FL350. The Airbus 320 was crossing the sector 1000ft above the aircraft in conflict, at FL370. The simple solution would be to climb or descend one of the aircraft. However, the other aircraft restricts a climb solution or a descend solution. Unless the ATCO intervened, separation was lost at around 05:34 (5 nm between the two aircraft and closing). The closest point of approach (CPA) was 0 nm and occurred 05:59 into the scenario.

The reason for using simple, generic, scenarios with only one conflict situation was to simplify knowledge elicitation in the debriefing and analysis of eye tracking data. The use of only one conflict situation means that the collected eye tracking data mainly reflects this one situation, making it less prone to noise from overlapping processes of e.g. dealing with multiple conflict situations. The conflict scenario was typical for the type of situations that ATCOs in training receive as an introduction to solving conflicts. It was designed to allow for exploring different solutions. The student is encouraged to test different solutions and understand that it can be done in different ways.

D. Procedure

Two participants each were invited to the same working day (8 hours). As mentioned above, this study was a part of a larger study, involving a total of six conflict scenarios per participant. The simulation started with the administration of consent forms, a demographics questionnaire, and simulation briefing. In a training scenario, the ATCOs were trained and guided by an instructor in the use and functionality of the simulator. Following the training scenario, participants accomplished all conflict scenarios. Scenario order (of all six scenarios) was varied between participants according to a Latin square randomisation to avoid learning effects. The calibration of the eye tracking system was conducted using a calibration mask with six calibration points on the radar screen prior to a scenario.

A debriefing session (approx 30 min) was held after the participant had completed the simulation. The steps of the session can be briefly summarized as follows:

1) **General Explanation** - Semi-structured interview on how the participant detects and solves conflicts in general (without video playback).
2) **Think Aloud Playback** - Playback of the eye-tracking of the reference scenario for the participant with comments about the intention, information seek and other

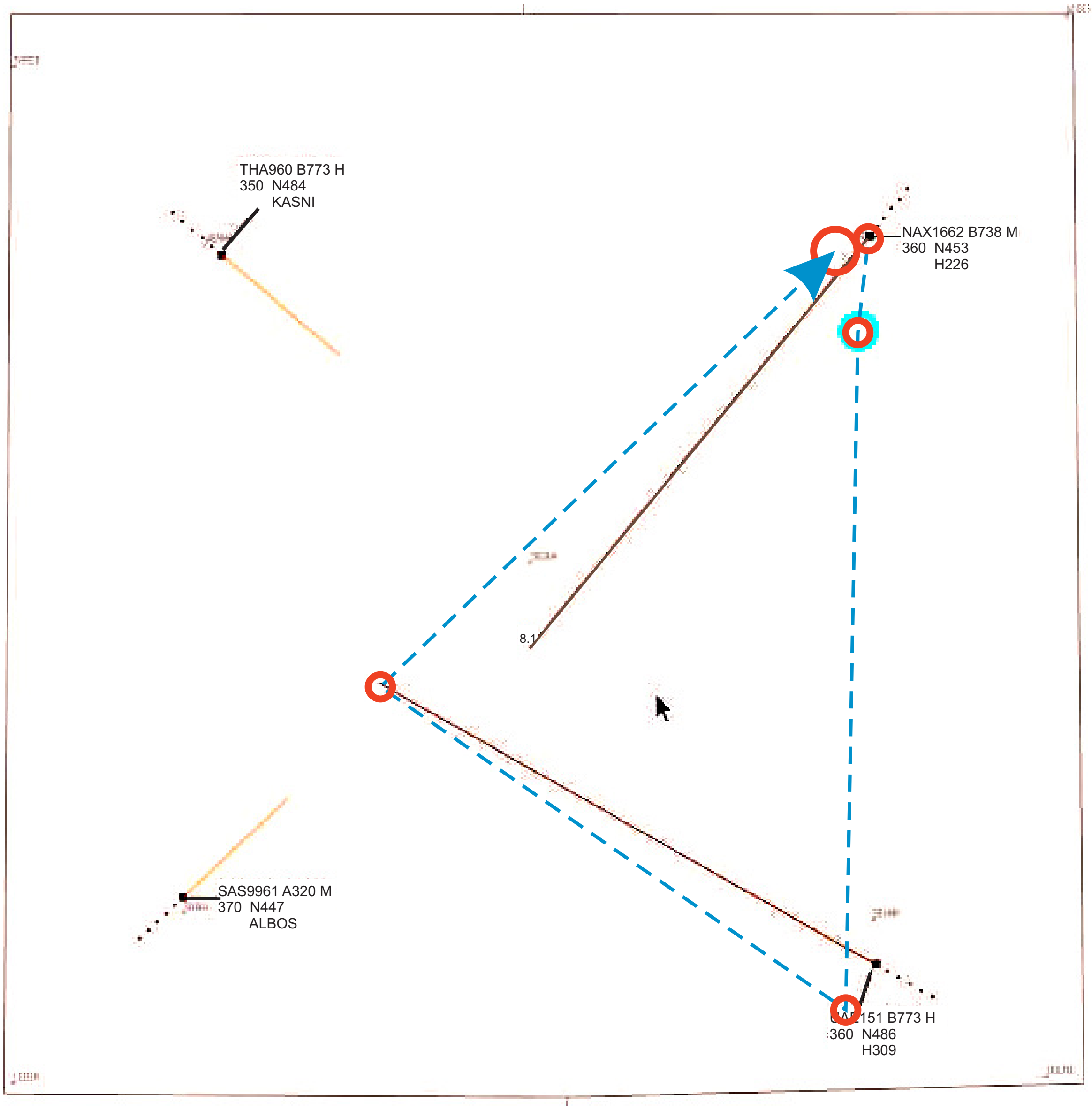

Figure 2. Conflict situation with annotated triangular ATCO scanpath (in blue dashed lines), fixating the conflicting movements and the closest point of approach (fixations in red circles).

factors. The participant could pause the video at any time for explanations.

During the first step, general explanation, ATCOs were asked to describe openly how they detect and resolve conflicts concerning. The questions were:

1) ”How do you find the conflicts?”
2) ”Which solutions do you consider?”
3) ”What factors do you consider for making a decision?”
4) ”What information did you look for?”
5) ”How fast do you make your decision?”

During the general explanation, the semi-structured approach allowed the questions to be phrased in a way that corresponded to the specific situation and traffic context to which the participant was referring. This encourages participants to speak freely about their personal approach to detect and resolve conflicts and helps them to be explicit, comment on their own behavior, and think out loud. We considered this step as a training for learning to think aloud, where participants are familiarized with the expected outcome of this exercise. This can also be seen as preparation for the next step, where unnecessary interference can then be avoided during playback. The comments were documented and transcribed as notes.

During the second step, the playback, the participant was shown his/her own eye-tracking video recording of the conflict scenario. The participant was instructed to think aloud and comment on his or her own actions and plans. An audio recorder was added to capture what was said during the playback to facilitate post-briefing analysis. Statements and audio recordings were transcribed and analyzed to extract cues used, and specific context. In addition, the results were classified using the CLC model.

IV. Results

The statements of 13 participants were collected, the notes and voice recordings merged and allowed for an extraction of the cues. From the extracted cues, a consolidated set of decision cues was determined as shown in Table I. This was to create a unified set of cues for harmonizing the range of terms used by the participant while commenting openly their own behaviour. An additional measure to sort is the classification of the cues that are used depending on the mentioned intention and the situation context. The statements helped to identify clear indications that ease the classification to a certain work step.

TABLE I. Decision Cues: Information, Timing and other Cues

Cues	Description
Flight Level	The current Flight Level, displayed by the radar label
Destination	Flightplan Information as displayed in the radar label.
Flight Route	Flight Route or Flight Legs as a series of visually connected Waypoints
Approaching Traffic	Traffic in adjacent sectors, approaching the current sector.
Expected Climb	This cue involves information about a foreseen climb request of a movement.
Flight plan	Flight plan Information, providing destination, route and flight level.
Predicted ToD	The distance to the destination airport where an exit level request can be expected.
WPYs	The next WPYs along the Flight Route
PSMD	Predicted Seperation Minima Distance - The seperation distance at the closest point of approach, predicted on current information available. The information gathering might be supported by the use of tools, such as the septool, the highlighted notification in the MTCA-conflict window or a simple bearing vector.
Traffic Complexity	The subjective recognition of the traffic complexity in the sector, involving the number of movements and the workload resulting from this. If used for the timing of solution implementation, implementation might be delayed or omitted during low complexity traffic situations. This because separation distance at CPA might shift advantageously.
Expected Change Level Request	Information about a foreseen change request of the flight level
Wind	Wind information as displayed by the weather situation or as an experience deviation between heading and course over ground.
Rate of Descent	The rate of descent as displayed by the radar label
Speed	The current speed as displayed by the radar label
Earliest	Just as early as possible regardless of any other factor.
Conflict Window	Predicted conflict as displayed in the conflict window and calculated by the Medium Term Conflict Detection

Table II shows the participants' statements of the cues, coded using the consolidated set and classification scheme from the CLC. Each participant comprises one row. The statements converge among all participants that some routines of CD&R are indeed trained patterns and considered as standard work habit. The classification of the work steps in the CLC was supported by the following indicators, which provide distinctive time points of transitions between the work steps, referred to as "distinctive transition indicators":

- Conflict detection was indicated by the the activation of the septool, used by all participants to highlight the conflict for further processing. The septool provides an unambiguous indication about the of closest point approach between aircraft. Air traffic controllers use it to track the continued progression of separation distance and ensure that the conflict remains in view throughout the conflict life cycle as a prospective memory reminder.
- The clearest indication of solution implementation is the communication of the solution/clearance to the pilot.
- Conflict resolution is considered complete when the septool is deactivated. The timing of these events allow for a classification that follows the sequence of steps through the CLC.

A particular decision cue was considered "solution preference" which describes a participant's tendency toward a particular solution.

Table II shows the decision cues mentioned by participants, broken down by the CLC's work steps and the associated keywords. The implementation of the solution is not considered at this point, since the implementation itself does not include any decision support, but only the technical and procedural compliant implementation of the previously selected solution. The distribution of the cues show intersections across participants, such as the flight level for identifying conflicts (12 of 13 participants).

A rather large amount of cues were used for conflict solution probing, setting the Predicted Separation Minima Distance (PSMD), as the most mentioned cue (12 of 13 participants). Some participants indicated that no action is required if the PSMD is less than 5 NM if the wind effect is expected to extend the distance to more than 5 NM plus an additional margin during the approach. This solution is preferred only in low traffic complexity situations where participants have the ability to monitor the progress and potentially intervene if the plan is not successful. Wind was mentioned by 4 of 13 participants.

After PSMD, Predicted TOD and Flight Route each was mentioned by 7 of 13 participants. 4 of 13 participants mentioned they would like to have the conflict solved as fast as possible. An equal number indicated that it depends on the complexity of the traffic and workload and retain the option of implementing a solution at a later time. Concerning the solution preference, "direct to" clearances was the preferred solution at hand (11 of 13 participants). This result can be explained by the tendency to keep the pilot's effort as low as possible and to rely on solutions where a predefined WPY can be selected in the FMS route plan.

TABLE II. Results on Decision Cues, including Information, Timing and Other Cues, Classified using the CLC

No.	Conflict Detection Information Cues	Conflict Solution Probing					Solution Monitoring Information Cue
		Information Cues	Timing Cues	Solution Preference (Decision Cue)			
				Direct to	Change FL	Turn Heading	
1	Approaching traffic Flight Level	Flight Plan Predicted ToD Expected Climb Flight Levels Flight Route WPYs PSMD	Traffic Complexity	First			
2	Flight Route Expected climb Flight Level	Predicted ToD Expected Climb PSMD Flight Route	Earliest	First			PSMD
3	Flight Level	Wind Predicted ToD Destination PSMD	Earliest	First when High Traffic Complexity		First when Low Traffic Complexity	
4		Traffic Complexity PSMD	Earliest	First	Second		PSMD
5	Flight Level	PSMD	Traffic Complexity		Second	First	PSMD
6	Flight Level	PSMD Predicted ToD Expected Change Level Request Destination Wind Flight Route	Traffic Complexity		First when High Traffic Complexity	First when Low Traffic Complexity	PSMD
7	Flight Level Destination	PSMD Flight Route Destination		First when High Traffic Complexity	Second	First when Low Traffic Complexity	
8	Flight Level Approaching Traffic	PSMD		First			PSMD
9	Flight Level Flight Route	Wind Rate of descent Destination Flight Route Traffic Complexity PSMD		First			PSMD
10	Flight Level Flight Route	PSMD Wind		First	Second when High Traffic Complexity	Second when Low Traffic Complexity	PSMD
11	Flight Level Approaching traffic Flight Route WPYs	Predicted ToD Flight Plan	Earliest	First	First when Destination is close		
12	Flight Level Flight Route	Predicted ToD Flight Route PSMD	Traffic Complexity	First		Second	PSMD Speed
13	Flight Route WPYs Conflict Window	Predicted ToD Flight Plan Flight Route WPYs PSMD		First			PSMD

As second solution, change “flight level” and “turn heading” are equally preferred and depend more on the situation, e.g., when the destination is close and a descent to a lower flight level will meet the nearing exit flight level request. For solution monitoring, the PSMD is the choice for following up the solution for 9 of 13 participants.

V. DISCUSSION

The interviews provided insight into the decision-making logic of air traffic controllers who sample cues to decide on a solution to the conflict situation at hand. The results in Table II show that participants were able to think aloud as described in the RTA method, and thus were able to give us the cues they thought they used during the decision-making for CD&R. The cues could be classified into the work steps of the CLC. This is achieved with the help of the “distinctive transition indicators” (see chapter IV), which mark the transitions between the work steps. Another helpful approach was the use of the consolidated set of cues, which helped to clarify the wide range of terms used for the decision cues.

The rather wide range of cues used in the search and probing for solutions could indicate the rather complex task and variety of solutions from which it is necessary to find a suitable solution that best fits the situation. Compared to the other work steps, conflict solution probing appears to be the most demanding task among the work steps, measured in terms of the decision cues included for this purpose. This is not surprising, since it requires the greatest competence in planning and anticipating the possible solutions. When comparing the participants, a large interindividual variance between the participants can be observed. Interestingly, such variances could be expectations based on previous experiences i.e. expected change level requests, or the desire to search for contextual information i.e. destination, for solution probing. Another explanation could be that controllers experience a highly individualized development of decision-making competence, as there is no standard defined beyond the Standard Operating Procedures that specify decision-making in detail.

There are also some limitations of the chosen study approach to mention. The open-ended RTA questioning method used may lead participants to mention only the cues they consider most important. This is not surprising at this point in the study as this may be explained by the subjective perception on the own work behaviour, even though the playback is shown. If even elementary decision cues such as “speed” are not picked up, the participant may not consider them relevant in this simple conflict scenario. In another scenario they might be. Another point is that the interview technique used does not provide ultimate evidence of external validity. Rather, the findings reflect the consensus of statements while interpreting them in the scope of a CLC. The variance of the data is quite high, and not captured to the full extent when relying only on the data from 13 ATCOs. The conflict resolution sounding step requires a larger number of participants to reliably narrow down the true number and variance of decision cues. Concerning the reference scenario, the ATCOs were given the opportunity to comment on the simple conflict scenario per video playback, but no daily realistic scenario. At this point, it was obviously the best approach to start with simple means, with an eye to a later continuation with more realistic scenarios involving multiple conflicts occurring simultaneously. Further, it should be noted that the number of statements increased with the amount of time the ATCO spent analyzing and interpreting the video playback. This indicates the effort spent in recalling the situation in the simulator and finding reasonable explanations for what the video playback shows.

An interesting finding is that some information cues rely on the compilation of several other information cues, such as the predicted top of descent that relies on information about the flight level and the distance to the destination, among others. Such predictions are performed mentally whereas the PSMD is a compiled information cue that is calculated by a digital assistance. The set of decision cues presented here show that humans and automation assistance complement each other in the task of processing elementary information and refining it into higher-level information. Although definitive proof can only come from subsequent closed-ended interviews, we believe the most important finding is that the steps along the CLC and the decision cues used are correlated. We conclude that the identified decision cues clearly indicate the work step and are suitable for use as classifiers. In this way, we may be able to identify the CLC’s work step and the related intent based on work patterns observed using eye-tracking and other measurements.

As another point of development, we propose that solution implementation and solution monitoring iterate without the other two steps of conflict detection and solution probing. This was observed when the participant mentioned and comment on solutions that involves the implementation of a series of clearances at pre-planned points of time. This could be, for example ”resume own navigation”, where the participant gives the clearance to resume to the original flight plan route after being vectored for conflict resolution. A corresponding extension of the CLC is proposed in Figure 1, which uses the yellow arrow to indicate the possibility of dividing the resolution into a series of actions, reiterating in a smaller circle. These are implemented according to a predefined plan at specific points in the progress of the situation and monitored accordingly.

The results of Palma Fraga [9] can be partially confirmed. Regarding conflict detection, speed was not so much important, but mainly the flight level is confirmed. The preferred solution here was clearly in the direction of “direct to” clearances, while altitude change or vectoring was the favorite described by Palma Fraga.

A. *Context specific decision making*

CD&R problems are inherently context dependent. The results in this study, i.e. the work pattern cues for CD&R and conflict resolutions, are artifacts derived from the specifics of the stimuli provided (i.e., reference scenario). For instance, the scenario was designed to purposefully constrain vertical solutions. As such, the focus in finding a solution to the conflict was biased toward a heading solution. This does not mean that the cues identified herein does not apply to other conflict situations.

VI. CONCLUSION AND OUTLOOK

This paper presents findings demonstrating the relationship between ATCOs' work patterns, decision cues used, and intentions during the step-by-step approach to conflict detection and resolution. The central results obtained are decision cues used along the work steps of the Conflict Life Cycle-model, summarized in Table II. The main highlights are summarized below:

- 16 decision cues were found of which 13 were information cues. 6 information cues in the conflict detection phase; 11 in the conflict solution probing phase; and 2 in the solution monitoring phase.
- The results show that the "conflict resolution probing" step is the most challenging task because it contains the most decision cues. The high inter-individual variance in the cue composition of this step indicates a high degree of individual skill development on which the adoption and selection of conflict solutions is based.
- The results show a quiet diverse distribution of decision cues along the work steps with inter-individual intersections and variations.
- The work steps appear to be distinguishable based on their set of decision support tools and the resulting work pattern.

A verification of these results by means of closed-end interviews is outstanding that shall give further proof to these results. The major finding is that used decision cues differ clearly from each other depending on the CLC-work step and the intention. As such, these results can support data-driven review of ATCO-applied work patterns and retrospective identification of intent based on patterns. The classification of intention by means of empirically measured work pattern might become possible. Comparing the time pre- and post-automation using this approach reveals the changes in workflow, making it possible to assess the impact of the changes on decision logic and safety. As future continuation, applications might rely on such a classification, allowing for quantification of workload by means of their spare time left for monitoring general traffic situation.

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REFERENCES

[1] L. Meyer, Å. Svensson, M. Peukert, S. M. Luengo, J. Lundberg, and B. Josefsson, "Classification of safety-relevant activities by using visual scan pattern in airport control operations," in *Engineering Psychology and Cognitive Ergonomics*, D. Harris, Ed. Cham: Springer International Publishing, 2019, pp. 381–395.

[2] Å. Svensson, "Analysis of work patterns as a foundation for human-automation communication in multiple remote towers," in *Twelfth USA/Europe Air Traffic Management Research and Development Seminar*, 2017.

[3] C. Westin, K. Vrotsou, A. Nordman, J. Lundberg, and L. Meyer, "Visual scan patterns in tower control: Foundations for an instructor support tool," in *SESAR Innovation Days*, 2019.

[4] W. Pawlak, C. Brinton, K. Crouch, and K. Lancaster, "A framework for the evaluation of air traffic control complexity," in *Proc. AIAA GNF Conf.*, San Diego, CA, 1996.

[5] J. Lundberg and B. J. Johansson, "A framework for describing interaction between human operators and autonomous, automated, and manual control systems," *Cognition, Technology & Work*, vol. 23, no. 3, pp. 381–401, 2020.

[6] J. Howells, "Tacit knowledge," *Technology Analysis & Strategic Management*, vol. 8, no. 2, pp. 91–106, 1996. [Online]. Available: https://doi.org/10.1080/09537329608524237

[7] G. Klein, "A naturalistic decision making perspective on studying intuitive decision making," *Journal of Applied Research in Memory and Cognition*, vol. 4, no. 3, pp. 164–168, 2015.

[8] Z. Guan, S. Lee, E. Cuddihy, and J. Ramey, "The validity of the stimulated retrospective think-aloud method as measured by eye tracking," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ser. CHI '06. New York, NY, USA: Association for Computing Machinery, 2006, p. 1253–1262. [Online]. Available: https://doi.org/10.1145/1124772.1124961

[9] R. Palma Fraga, Z. Kang, J. M. Crutchfield, and S. Mandal, "Visual search and conflict mitigation strategies used by expert en route air traffic controllers," *Aerospace*, vol. 8, no. 7, 2021. [Online]. Available: https://www.mdpi.com/2226-4310/8/7/170

[10] ERASMUS, "Final report. en route air traffic soft management ultimate system," European Commission, Report ERASMUS–WP422-TRANSITION-PLAN-V1.0, 2009.

[11] B. Hilburn, "Cognitive complexity in air traffic control: A literature review," CHPR BV, Report 04/04, 2004.

[12] K. Eyferth, C. Niessen, and O. Spaeth, "A model of air traffic controllers' conflict detection and conflict resolution," *Aerospace Science and Technology*, vol. 7, no. 6, pp. 409–416, 2003.

[13] E. M. Rantanen and A. Nunes, "Hierarchical conflict detection in air traffic control," *The International Journal of Aviation Psychology*, vol. 15, no. 4, pp. 339–362, 2005.

[14] P. Averty, K. Guittet, and P. Lezaud, "An ordered logit model of air traffic controller's conflict risk judgment," *Air Traffic Control Quarterly*, vol. 16, no. 2, pp. 101–125, 2008.

[15] S. Loft, S. Bolland, M. Humphreys, and A. Neal, "A theory and model of conflict detection in air traffic control: Incorporating environmental constraints," *Journal of Experimental Psychology: Applied*, vol. 15, no. 2, pp. 106–124, 2009.

[16] S. Fothergill and A. Neal, "Conflict-resolution heuristics for en route air traffic management," *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 57, no. 1, pp. 71–75, 2013. [Online]. Available: http://pro.sagepub.com/content/57/1/71.abstract

[17] X. Xu and E. M. Rantanen, "Conflict detection in air traffic control: A task analysis, a literature review, and a need for further research," in *Proc. 12th ISAP*, Dayton, OH, 2003, Conference Proceedings, pp. 1289–1295.

[18] C. Borst, R. M. Visser, M. M. van Paassen, and M. Mulder, "Exploring short-term training effects of ecological interfaces: A case study in air traffic control," *IEEE Transactions on Human-Machine Systems*, vol. 49, no. 6, pp. 623–632, 2019.

[19] S. N. McClung and Z. Kang, "Characterization of visual scanning patterns in air traffic control," *Intell. Neuroscience*, vol. 2016, Apr. 2016.

[20] K. Vrotsou and A. Nordman, "Exploratory visual sequence mining based on pattern-growth," *IEEE T. Vis. Comput. Gr.*, vol. 25, no. 8, pp. 2597–2610, 2019.

[21] J. Lundberg, J. Johansson, C. Forsell, and B. Josefsson, "The use of conflict detection tools in air traffic management: an unobtrusive eye tracking field experiment during controller competence assurance," in *Proceedings of the International Conference on Human-Computer Interaction in Aerospace*, 2014, pp. 1–8.

[22] E. Hollnagel, *The ETTO Principle: Efficiency-Thoroughness Trade-Off: Why Things That Go Right Sometimes Go Wrong*, 1st ed. CRC press, 2009. [Online]. Available: https://doi.org/10.1201/9781315616247