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The Intervention Trigger Model: Computational Modelling of Air Traffic Control

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Abstract

Two models of hierarchical decision making in a conflict detection task were compared (Niessen, Leuchter, & Eyferth, 1998; Rantanen & Nunes, 2005) using eye-tracking data. 30 experienced air traffic controllers individually processed a series of 56 trials. In each trial, 15 participants had to decide whether two aircraft displayed on a simulated radar screen would be in conflict, i.e., whether their horizontal and vertical distances would eventually violate legal separation rules, the 15 others had to decide whether an intervention would be required to avoid a conflict. Results showed that none of the two models could fully account for the data. These results led us to produce a new model of hierarchical decision-making, implemented in the cognitive architecture ACT-R 6.0.

Keywords: Air Traffic Control; Computational modelling; Decision-making; Eye-tracking.

Introduction

Air traffic controllers (ATCos) are in charge of the flow and security of the traffic in the sector under their responsibility. According to Seamster, Redding, Cannon, Ryder, and Purcell (1993), an important subtask for ATCos is to maintain situation awareness (Endsley, 1995) so as to determine events that require an action, in particular to prevent aircraft conflicts. A conflict is defined by the simultaneous violation of two safety rules: two aircraft must always remain separated (1) at least by 5 nautical miles (NM) on the horizontal plane¹; and (2) at least by 1000 feet on the vertical plane. ATCos have to detect potential conflicts and to take any necessary action to avoid them. Recently, Stankovic, Raufaste, & Averty, 2008 provided a three-variable model that explains about 50% of the variance in experts' conflict judgments. Yet, it is not a process model. Bisseret (1995) argued that ATCos detect conflicts on the basis of a lexicographic decision rule. Despite this idea was confirmed by various studies (e.g., Niessen et al., 1998; Niessen & Eyferth, 2001; Eyferth, Niessen, & Spaeth, 2003; Rantanen & Nunes, 2005), authors do not agree about the structure of the lexicographic tree. This paper brings new data that enlighten the order of micro-decisions involved in conflict detection. Our propositions were encapsulated in a new model of conflict detection. It was implemented in the ACT-R cognitive architecture (Anderson & Lebiere, 1998; Anderson et al., 2004; Anderson, 2007) and satisfyingly fitted RT data.

¹Here, we focus on the case of "en route" traffic (i.e., not around taking-off and landing) at constant altitudes.

Two different strategies for conflict detection

Putative decision-making strategies have been proposed, mainly based on cues such as aircraft altitudes, headings, or ground speeds (Bisseret, 1995; Niessen, Eyferth, & Bierwagen, 1999; Rantanen & Nunes, 2005). On the radar screen these cues are grouped in data blocks, close to each aircraft representation. Two decision-making strategies using those cues are now recalled.

The MoFL model. Niessen et al. (1998, 1999) studied how the data displayed on a radar screen were selected. Based on empirical data, they devised a post-hoc global model of traffic control ("Modell der Fluglotsenleistungen" that embeds the following strategy for conflict detection.

1. If aircraft are on crossing airways or on the same airway, next step; otherwise "no conflict" and exit;
2. Are aircraft on different altitudes and not vertically moving? If yes, "no conflict" and exit; otherwise next step;
3. A mental anticipation of the future positions of the aircraft is performed, using "speed vectors"². It provides an estimate of the likelihood of a conflict.
4. Anticipation accuracy is estimated from the range of the anticipation and, when a potential conflict is suspected, the time available before conflict occurrence.
5. According to their evaluations controllers can make a decision: If the anticipation is deemed safe, then decide accordingly and exit; Otherwise, further monitoring is requested.

The hierarchical model. More recently, Rantanen and Nunes (2005) proposed a model more precisely focused on conflict detection in en-route controllers. To test their model, the authors asked ATCos to decide whether or not two aircraft displayed on a simulated radar screen were actually in conflict. They proposed that ...

1. If altitudes are vertically separated by at least 1000 feet, then "no conflict" and exit; otherwise next step;
2. If the aircraft are on diverging trajectories or if the aircraft have parallel headings and a sufficient horizontal separation, then "no conflict" and exit; otherwise next step;

²A speed vector is a line showing the aircraft future positions during the next minute(s) to come.

3. If the aircraft cruise “at the same speed and have a distance difference to the point where their trajectories intersect that is at least the minimum required lateral separation” (p. 345), then exit; otherwise last step;
4. Compute the minimal distance at the Closest Point of Approach (hereafter referred to as Dt_h , following the terminology of Stankovic et al., 2008). If Dt_h is below the minimum lateral separation then decide “conflict”; otherwise, exit.

The differences between the models raise at least two issues. The MoFL model suggests that divergence is considered first. Thus, altitude should not be considered in case of divergent trajectories. To the contrary, Rantanen and Nunes’ model—which we will denote by the “RN model”—suggests that Altitude is considered first, then, only in the case where altitude are the same, trajectory angles would be considered. Another feature distinguishes the two approaches: Rantanen and Nunes consider conflict judgment whereas in the MoFL model, the decision to intervene or not is the outcome of the conflict-analysis step. This difference might be a source of process variations because conflict judgments are not the normal product of a controller and it can be argued that conflict judgment require more deliberate processing, which could explain more attention paid to symbolic information such as altitude. We propose a new experiment (1) to study the order of information acquisition; (2) to check if asking conflict judgments (“Conflict” vs. “no conflict”) or intervention decisions (“would intervene” vs. “would not intervene”) affects data acquisition; (3) to provide data for fitting a computational model of the task.

Hypotheses

Lexicographic strategies can be characterized by the order of processing pieces of evidence. Also, criteria coming first in the decision tree should be associated with faster responses. Hence, RTs and eye-tracking data seem relevant to study a lexicographic strategy.

Altitudes and aircraft representation. According to the MoFL model, the first information intake should be the aircraft headings to assess the divergence of the trajectories. Only after should altitudes be looked at. Following the Rantanen and Nunes (2005)’ model, the first information intake should concern flight levels, so as to compare altitudes. For same-altitude pairs of aircraft, trajectory vergence would then be tested. Ideally, one would test convergence by tracking fixations of the aircraft representations (including the speed vector). However, testing divergence may not always require a specific gaze at aircraft representations. Indeed, parafoveal vision might be sufficient to inform the controller about divergence. Finally, Dt_h would be evaluated. By definition Dt_h corresponds to the distance between the two aircraft at t_h , the moment when they are closest on the horizontal plane. At this very moment, the two aircraft should be in the surroundings of the intersection point unless it is

quite obvious that there is no conflict. Thus, in experimental scenarios with enough uncertainty to require computing of Dt_h , the intersection point of the two trajectories will likely be gazed at. Thus, in a lexicographic approach, the intersection area must be looked at in last position.

RTs. The order of taking evidence into account should affect reaction times: in scenarios that require deeper investigation through the decision tree, reaction times should be longer. Thus, the two models predict an order of increasing RTs that parallels the order of fixations. In particular, as regards the first and second cues, the predictions derived from the MoFL and the RN model are opposite: *ceteris paribus* the former predicts shorter RTs for divergent trajectories—regardless of altitudes, whereas the latter predicts shorter RTs for trajectories of different altitudes—regardless of divergence. In summary, if we note “SA” and “DA” the same and different altitude scenarios, “Div” the diverging angle trajectories, and “other” the non diverging trajectories, the RT patterns predicted by the two models are as follows.

MoFL: DA-Div = SA-Div < DA-other < SA-other

RN: DA-Div = Da-other < SA-Div < SA-Other

It can be divided into a part common to the 2 models and a part that distinguishes the two models. The common part is DA-Div < SA-other. The part that discriminates is:

MoFL: SA-Div < DA-other

RN: Da-other < SA-Div

Finally, the RN model predicts that, among the SA scenarios, those where aircraft have the same speed will be processed faster than those where aircraft speeds are different.

Experiment

Method

Participants. 30 experienced controllers in two groups participated on a voluntary basis, with experience defined as the number of years after the graduation from the ENAC: $N = 15$, age $M = 36.6$ ($SD = 8.8$), experience $M = 9.7$ ($SD = 7.1$); and $N = 15$, age $M = 38.9$ ($SD = 7.1$), experience $M = 13.1$ ($SD = 7.6$).³

Apparatus and procedure. A simulated radar screen displayed the pairs of aircraft. Each aircraft (see Figure1) was represented by a triangle shape continued by a speed vector that indicated the heading and the anticipated location after a 1mn lag. The length of the speed vector was directly proportional to the aircraft speed. A data block close to each aircraft presented symbolic information. From top to bottom: horizontal speed in knots, denomination (the “call sign”), altitude in flight levels⁴.

³the French national civil aviation training institution

⁴1 FL= 100 feet.



Figure 1: Screenshot of an aircraft cruising at the constant altitude of FL 410. Its speed is 440 kts. A scale representing 5NM was presented at the bottom left of the display. Here, dashed lines represent the areas of interest (AOI) used to compute eye fixations, but they were not visible by participants.

An ASL501 eye-tracker from Applied Science Laboratories was used, set to a sampling rate of 50Hz. After the initial calibration, the instructions were displayed. Participants were told to judge if a pair of aircraft would be in conflict should no action be done. The experiment comprised six practice trials with no feedback, then 56 experimental trials. Time was limited to sixty seconds per trial. All along the trials, aircraft positions were refreshed every ten seconds. To control for the initial gaze location, a white cross was presented first. The aircraft representations were displayed by the experimental program only after it had detected that the cross—at mid distance between the two aircraft—was being fixated.

Task. Half of the ATCos had to tell whether they would intervene, the others had to tell whether the aircraft were in conflict. For the sake of simplicity and to focus on the process of conflict detection, participants were instructed that altitudes, speeds and headings were constant. They were asked to produce their judgment as accurately as possible and to give their responses as soon as they were sure of their diagnosis.

Variables and analysis. A total of four independent variables were used in a repeated-measures design (7 Angles of convergence \times 2 Altitudes \times 2 Speeds \times 2 Dt_h), giving 56 scenarios. The parallel headings corresponded to the angles of convergence 0° (one aircraft followed the other), and 180° (aircraft in opposition). Converging angles were 45° , 90° , 135° . Diverging angles were 45° and 90° . Altitudes could be either equal or different by at least 10 FL. Speeds were either equal or different by 10 to 60 knots. Horizontal separation at the closest point of approach (Dt_h) was either

2.5 NM or 7.5 NM. Of the 56 scenarios, 9 offered a conflict configuration. Each participant viewed the complete set of scenarios only once. In addition to the repeated measures, the design comprised a between variable: 15 participants, were asked to provide a conflict judgment (“conflict” vs. “no conflict”) and 15 participants had to provide an intervention judgement (“would intervene” vs. “would not”).

DVs were RTs in ms, and eye-tracking data about 4 areas of interest (AOI): the aircraft representation (including its speed vector), flight levels, symbolic speeds and the crossing point area. A representation of these AOI can be found in Figure 1. At the trial level we computed the rank of visit to each AOI. Eye tracking data from the various scenarios were also aggregated according to the hierarchical model criteria: 28 trials for each of the same and different altitudes conditions (SA and DA) were grouped into 12 trial for convergent headings, 4 for each of the 0° and 180° angles, and 8 for divergent angles. Within each aggregation level we computed the median rank of first visit and the proportion of cases where each AOI was neglected (not visited at all).

For each participant we computed the median rank of visit to each AOI. Friedman nonparametric tests for k -paired groups were used to test the order of AOI visits. Wilcoxon tests for two paired groups were used to test differences between AOIs ranks.

Results

Fixations. Results on rank comparisons can be found in the upper part of Table 1. Friedman tests were significant for all conditions ($\chi^2(2, N = 30) > 13.00$; $p_s < .01$). Altitude was the first information intake in all situations excepted for divergent scenarios. This result corroborated the RN model and disconfirm the MoFL model predictions. Indeed, even in the conditions of divergent trajectories, aircraft representations were not looked at in first place (the best rank was second in both DA-Div and in DA-others conditions). Within SA condition (SA-Conv, SA- 0° and SA- 180°), one can see that rank orders differed with the angular configuration of trajectories. For SA-Conv conditions, altitudes were first, speeds second, intersection third and aircraft fourth. For 0° angle, altitudes were first, speeds second and aircraft third. For 180° angle, altitudes were first, and symbolic speeds and aircraft shared the third rank.

Response times. We averaged the response times according to the scenario categories defined in the hypotheses section: DA-Div, SA-Div, DA-SS and DA-DS (as DA-others), SA-SS and SA-DS (as SA-others). A six-factor ANOVA was significant ($F(5, 140) = 160.33$; $p = .001$; $MSE = .05$). Results are shown in Figure 3. Post-hoc comparisons showed no difference between:

- DA-Div and SA-Div scenarios,
- DA-SS and DA-DS scenarios,
- SA-SS and SA-DS scenarios.

Table 1: Median rank of first visit to AOIs. SA: same altitude; DA: different altitudes; Conv and Div= Convergent and divergent angles.

AOI	DA		SA			
	Div	Others	SA-conv	SA-0°	SA-180°	Div
Altitude	1.88	1.5	1.16	1.07	1.15	1.5
Symbolic speed	2.45	2.6	2.27	2	2.37	1.9
Aircraft	1.67	1.89	3.71	2.93	2.47	2.59
Intersection			2.85			

Table 2: Mean response times in seconds. SA: same altitude; DA: different altitudes; SS:same speeds; DS: different speeds; Div= divergent angles.

	Divergent angles				Not divergent angles							
	DA-Div		SA-Div		Different altitudes				Same altitude			
	M	SD	M	SD	DA-SS		DA-DS		SA-SS		SA-DS	
Judgment	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Conflict Dection	2.16	0.52	2.24	0.64	2.60	0.33	2.55	0.53	5.39	1.40	5.07	1.06
Intervention	1.98	0.45	1.91	0.48	2.52	0.52	2.38	0.48	3.75	0.72	3.98	1.02

Response times could be ranged as follow: $(DA - Div = SA - Div) < (DA - SS = DA - DS) < (SA - SS = SA - DS)$.

Instruction (i.e. providing a intervention judgment or a conflict judgment) had a significant effect on RTs ($F(1, 28) = 5.84$; $p = .02$; $MSE = 0.4$). Post-hoc pairwise comparisons showed that only in SA-SS and SA-DS conditions the « conflict detection » group response times were higher than the « intervention » group's.

Discussion

We contrasted two models of the conflict detection task, the MoFL model and the RN model. Divergent angles produced shorter reaction times than all others scenarios: divergence was the first information processed. In contrast, the RN model predicted that altitudes are processed before convergence, which is clearly not compatible with our data. The RN model also predicted that SA-SS scenarios should be processed faster than SA-DS scenarios. Post-hoc comparisons did not confirm this pattern. Our data were globally compatible with the MoFL model. Yet in the MoFL model the anticipation step amounts to evaluate the speed vector length without specifying how speed vectors are processed. Moreover, it is unclear how trajectory angles are accounted in decision strategies (except for divergent angles). One can be surprised that divergent aircraft scenarios provided fastest RTs while aircraft were only looked at late. We propose that when ATCos look at an aircraft altitude they also get the heading through parafoveal processing. As perceptual processing is faster than symbolic comparison, divergence can be processed before altitudes.

We now propose a new model of conflict intervention, which integrates the points above: the Intervention Trigger Model (ITM).

A new model and an implementation

This three-step model (see Figure 2) is compatible with our results. As in the Rantanen and Nunes model, it embeds the idea of a lexicographic processing where the next fastest decision criterion is investigated first. At the beginning of the process, the model is like the MoFL: when relevant, divergence is processed first. The second step is to compare altitude, and the third test is a series of processes leading to the estimation of the D_{th} . As soon as altitudes are compared, the model processes symbolic speed. Next, it pays attention to the aircraft representation. We suppose that aircraft representations aid ATCos who try to estimate the distance between both aircraft (0° or 180° cases) or between either each aircraft and the intersection point (convergent angle cases). ATCos would compute these distances to estimate the D_{th} . If the evaluation of the D_{th} is under the minimal horizontal distance of separation then ATCos should intervene, otherwise they need not intervene.

We assume that the D_{th} estimation depends on the angular configuration of the trajectories:

- when aircraft have the same heading (0°), knowing the relative position of the fastest aircraft is a relevant strategy. Indeed, if the fastest aircraft is ahead the slowest then there is no risk: the slowest aircraft will never catch the fastest one up. If the fastest aircraft is behind the slowest, the fastest aircraft will catch up the slowest, and then the controller will intervene.
- When aircraft are on opposite headings (180°), ATCos have to estimate the distance between the two trajectories. If this distance is below the separation norm, then the controller must intervene, otherwise he does not have to.

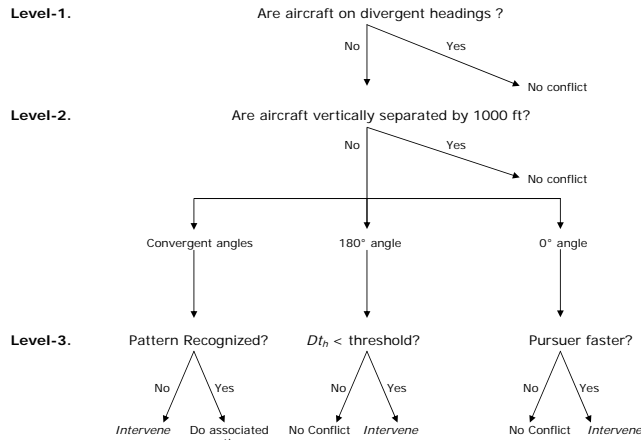


Figure 2: A model of Intervention Trigger in en-route air traffic controllers, as a function of altitudes, angles, relative speeds and D_{th} . “Pattern recognized” refers to known configurations that lead to an associated response. For example, one aircraft is by far closer to the intersection of the trajectories and also flies faster, which requires no intervention.

- When aircraft are on convergent headings, it is possible that ATCos learn to recognize a set of geometrical configurations as being a threat (or not). For configurations out of this set the controller would doubt and therefore might engage more deliberate processing of distance so as to gain accuracy. For example, if an aircraft is by far closer to the intersection point than the other aircraft, no further processing is required. Now, if two aircraft are at about the same distance from the intersection point, then the controller must intervene unless some very salient difference between speeds provides a simple solution.

Strategies included in the model

Perceptual processing and altitudes. The model starts to seek for altitudes. When the first altitude is encoded, the model also encodes the aircraft heading. It does the same for the second aircraft. Before comparing altitudes, the model compares the headings. If headings are divergent, the model exits the decision process. Otherwise, it recalls the altitudes kept in memory. If altitudes are separated enough, the model exits the process, otherwise it follows the next step.

Speed information intake. At this level, aircraft are at the same altitude and do not diverge. Then the model needs to know aircraft speeds for computing the D_{th} . The model encodes the two aircraft speeds and compare them. It encodes either which aircraft is faster or the fact that they have the same speed. As a function of the angular configuration of the trajectories it will make a decision.

- **Pursuit (0°).** As mentioned above, the strategy is to assess which aircraft is ahead. If the fastest aircraft is ahead, there

is no need to intervene. In the opposite, the fastest will catch the slowest up and the model will intervene.

- **Opposite headings (180°)** The model will assess the distance between the two lines. It will encode one aircraft trajectory. It will then move its attention to the second aircraft. Then it evaluates the distance between the encoded first aircraft line and the second aircraft. If this distance is below a criterion then the model requires an intervention, otherwise there is no need to intervene and the model stops the process.
- **Convergent headings.** The model will first assess the situation as a whole. If the configuration is recognized by the model, it immediately requires an intervention (e.g., aircraft are too close each other) or not (e.g., aircraft are enough separated). If the model cannot make its decision, it assesses the distances between each aircraft and the perceived intersection point of the trajectories. Afterwards, the two distances are compared to decide which aircraft is closer to the intersection point. If the fastest aircraft is the closer, there is no need to intervene, otherwise, the model will intervene.

Implementation and simulation

An ACT-R 6.0 implementation was built⁵ and tested against the scenarios and data from the Experiment reported here, limited to the intervention condition. 15 simulated subjects processing 56 scenarios each were simulated. Reaction times were recorded and aggregated as a function of the conditions of the scenarios (i.e., DA-Div, SA-Div, DA-others, SA-SS, SA-DS). All ACT-R parameters were set to the default values they have in the architecture, except Retrieval Threshold (-1.5) and Activation Noise (0.01). A total of 111 productions were included in the model. The correlation fit was $r = .994$, the mean deviation was less than 250 ms (Figure 3).

Conclusion and Perspectives

In this paper we reported an experiment that enabled us to clarify an incoherence between two models of decision-making in ATC. However, neither model could account for all the data. So we proposed a new model that takes advantages of the features of ACT-R architecture, in particular the interplay between perceptual and motor modules, and central cognition. Several computational models of the Air Traffic Control task exist (e.g., S. M. Lee, Ravinder, & Johnston, 2005; Callantine, 2005; Niessen et al., 1998; Taatgen, 2001, 2002; F. Lee & Taatgen, 2002) but few consider the details behind the triggering of interventions. Raufaste (2006) provided a conflict detection model based on Rantanen and Nunes (2005) model. This model differed from the current in the strategies used along the decision making process. For example, the perceptual processing of the divergence occurred first but was not effective until the model checked

⁵Annotated ACT-R model available at <http://w3.ltc.univ-tlse2.fr/raufaste/ACTR/ITM/>

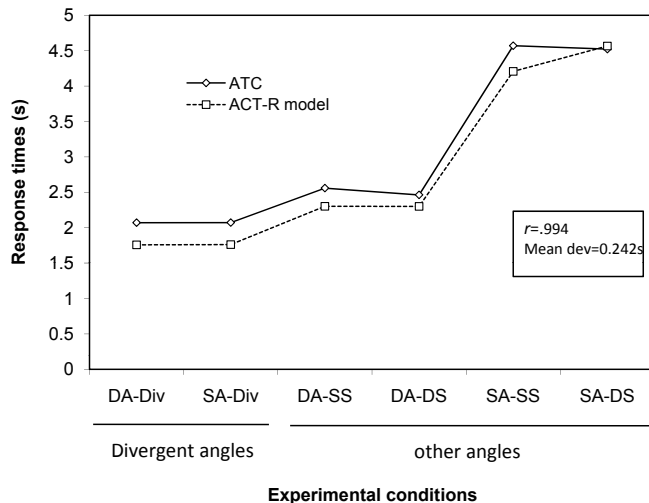


Figure 3: Response times as a function of scenarios

the vertical separation. Moreover, speed processing was first based on the comparison of the length of the speed vectors and not on symbolic speeds. Finally, this model could account for pursuit and opposite heading scenarios but convergent heading scenarios were not simulated. Thus, not only the current model has a better fit (the correlation fit in Raufaste, 2006, was $r = .92$ and the mean deviation was about 600ms) but it provides a more comprehensive modelling. Also, contrary to the previous model, no emphasis is placed on the process by which the crossing point of trajectories is computed, which is in agreement with the low number of fixations devoted to intersections reported here.

Obviously, the IT Model needs to be improved in many ways. For example, the sample of scenarios used for the experiment did not cover all cases of conflict. Many others experiments are needed to be able to describe a comprehensive set of likely strategies. Moreover, this model does not take in account individual differences. But undoubtedly, the main next step will be to take altitude changes into account.

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