

CONFLICT DETECTION IN AIR TRAFFIC CONTROL:
A TASK ANALYSIS, A LITERATURE REVIEW, AND A NEED FOR FURTHER RESEARCH

Xidong Xu and Esa M. Rantanen
University of Illinois, Aviation Human Factors Division
Savoy, Illinois, USA

A task analysis for a typical air traffic control conflict detection scenario is described. Two types of prediction components are identified, (1) a relative judgment (RJ) task with regard to which aircraft will reach the projected point of intersection first, and (2) a prediction-motion (PM) task estimating the time-to-collide if the aircraft will reach the intersection simultaneously. Also identified are several alternative strategies that can be potentially used by controllers to perform the RJ and PM tasks. Following the task analysis, a literature review on factors influencing the RJ and PM performance reveals that although there are a number of studies on controller performance in conflict detection, almost no one has studied how the controller actually performs the RJ and PM tasks. Finally, a number of potential research questions are proposed with an aim to shed new light on the human attention/cognition mechanisms involved in the prediction tasks in ATC and hopefully contribute to the knowledge base regarding motion prediction involving multiple objects or multiple tasks.

Introduction

Many air traffic control (ATC) job analyses consider prediction as one of the controller's core skills. For example, Roske-Hofstrand and Murphy (1998) conclude that although different ATC positions constitute different cognitive task requirements due to the different aircraft flight phases, task aids, and time constraints for each position, almost every such position demands mental projection or estimation. Prediction is also considered an important part of situation awareness (SA), which is considered to consist of three hierarchical phases: Level 1 SA, perception of the elements in the environment, Level 2 SA, comprehension of the current situation, and Level 3 SA, projection of future status (Endsley, 1995). In the ATC context, the controller needs to predict what will happen in the future based on Levels 1 and 2 SA to achieve Level 3 SA (e.g., two aircraft on converging courses will probably collide in three minutes if no measure is taken).

The task of conflict detection is very resource demanding. Indeed, midair collisions and near-misses have repeatedly occurred due to controller's inability to predict the loss of separation between aircraft (e.g., the midair collision between a Russian passenger plane and a British cargo plane over Germany in 2002). Prediction is largely dependent on spatial working memory to "compute" the future states of aircraft (Wickens, Mavor, & McGee, 1997). When relative positions of multiple aircraft need to be predicted, the controller's processing capabilities will be heavily taxed, thus limiting the accuracy of prediction. Understanding the underlying perceptual and cognitive mechanisms is therefore necessary in

order to identify the human limitations in conflict detection and to determine areas where automated aids are most beneficial.

Task Analysis

Although there are occasions where predictions involving more than two aircraft need to be made, we will for the sake of simplicity limit the discussion here to situations where only two aircraft are present. Consider two aircraft flying at the same altitude on straight converging courses, at constant velocities (see Figure 1). Assuming that both aircraft will maintain their current headings, airspeeds, and altitudes, they may collide at the projected intersection point on their extended trajectories. Note that for a more general case (3-D), the overlapping of two aircraft's positions on the horizontal plane is only necessary but not sufficient for the two planes to collide; the controller needs to perform predictions for the horizontal and the vertical planes at the same time. The prediction of the latter—given vertical speeds and current altitudes of the two aircraft— involves computation whether the planes will reach the same altitude at the time of the position overlap on the horizontal plane. Further, if instead of using a point as the criterion for collision we use a 5 nm and ± 1000 ft separation as the conflict criterion, the same reasoning would still apply. In this case, we will increase a point to a volume of space as the protected zone for an aircraft into which no other aircraft is allowed to penetrate.

Relative judgment and prediction-motion tasks. First, the intersection point in Figure 1 needs to be extrapolated, which is a relatively easy task for

straight and constant courses. Whether and when the aircraft will collide also need to be predicted, which are more complex tasks than the projection of the intersection point. Thus, there seem to be two additional predictive components involved in the above scenario. One is what is called the relative judgment (RJ) (Law, Pelegriano, Mitchell, Fischer, McDonald, & Hunt, 1993; Tresilian, 1995). For this kind of prediction, the controller needs to judge which aircraft will reach the extrapolated intersection point first. As long as it is determined that one will reach that point first, there will be no further prediction required (i.e., the two aircraft are deemed to be safely separated) so far as this pair of aircraft are concerned.

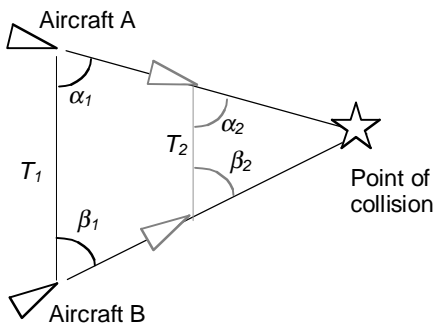


Figure 1. Two aircraft flying at the same altitude on straight converging courses at constant velocities.

However, if the two aircraft are predicted to arrive at the intersection point at the same time, there will be another predictive task: At what time will they be at the intersection or in collision (i.e., time-to-contact or TTC). This type of task is termed prediction-motion (PM) task (Tresilian, 1991; 1995). The RJ and the PR tasks are linked in the following way. The controller can perform the PR task first, the result of which (i.e., TTC) can naturally lead to the RJ conclusion (i.e., whether two aircraft will be safely separated or not). Or if the controller is in a position to perform the RJ task first, and the result shows the aircraft will be in conflict, then the controller needs to estimate the TTC. However, if the RJ result indicates that safe separation will exist, then the controller will not need to estimate the TTC.

Task performance strategies. The RJ task can be performed using several strategies. For instance, if the interior angles formed by the line connecting the current positions of the two aircraft and their respective trajectories are perceived to be constant over time ($\alpha_1 = \alpha_2$, and $\beta_1 = \beta_2$ in Figure 1), then the controller should have a good reason to believe that

the two aircraft will end up at the same position at the same time in the future. (Note that $\alpha_1 = \beta_1$ or $\alpha_2 = \beta_2$ are not necessary for a conflict to occur.) If, however, the interior angles are perceived to have changed over time, then it can be deemed that the aircraft involved will not collide with each other. In some special cases, the controller does not need to rely on these methods to perform the RJ task. For example, when two aircraft are perceived to be at the same distance to the intersection point and flying at the same velocity, the controller will know that they will be at the intersection point at the same time. In other words, the controller can take cognitive “shortcuts” to reach an RJ conclusion.

There are also several strategies with which to perform the PM task. The time at which an aircraft will arrive at a point in space, assuming a level, straight, and constant speed flight, is specified by the distance between the current aircraft position and that point and the speed of the aircraft. Therefore, as one of the alternatives, it is possible that the controller uses the so-called distance to speed ratio strategy to compute the TTC (Tresilian, 1991).

Let d_A and d_B denote the retinal distances corresponding to the actual distances to be traveled by Aircraft A and B, D_A and D_B , respectively. Additionally, let v_A and v_B denote the retinal velocities of the two aircraft corresponding to their actual velocities, V_A and V_B , respectively. For a two dimensional ATC radar display that is parallel or nearly parallel to the retina surface, it is easy to prove (by similar triangles) that the retina TTC for Aircraft A and B are the same as the actual TTC for the two aircraft, respectively. That is,

$$TTC_A = d_A/v_A = D_A/V_A, \text{ and } TTC_B = d_B/v_B = D_B/V_B.$$

Thus, the controller can independently determine, for the two aircraft, the TTC with the projected point of intersection, based on the retina distance to the retina velocity ratio (i.e., d_A/v_A and d_B/v_B).

Alternative to the distance divided by velocity strategy, the controller could possibly use the so-called tau strategy (i.e., optical variables method) to judge whether and/or when the two aircraft will collide (Tresilian, 1991; 1995). The “tau strategy” in its original formulation would be based on the relative expansion rate of the images of the objects moving in 3-D space. This cannot possibly be useful in ATC as this expansion rate tells nothing about when the two aircraft will collide, if the images of the aircraft are moving in 2-D space as is the case on a

plan-view ATC radar display. Note that the expansion rate, if it is present at all, will be very small. What are needed are not the expansion rates of the images themselves but the size of the gap between the images of the two aircraft and the shrinkage rate of this gap. Also note that it is not necessary to compute the distance between the two images; the visual angle subtended by the gap between the two images is sufficient. This visual angle divided by its rate of change specifies the TTC of the two objects (if they are on collision courses) (personal communication with Tresilian, Feb. 3, 2002).

Another probable strategy for the PM task is what is referred to as cognitive motion extrapolation (CME) (DeLucia & Liddell, 1998). According to this hypothesis, an observer may develop a cognitive model or representation of the object's motion at the initial stage of the motion, and then project the object's future motion based on that model. Errors in the estimated TTC are due to inaccuracy of the cognitive model. The major difference between the CME strategy and the other two strategies is that the former is characterized by an explicit spatial representation of the object's motion (time is only implicit), whereas the latter two involve an explicit temporal representation of the motion, where spatial representation is not necessary (DeLucia & Liddell, 1998).

Factors Influencing RJ and PM Performance

Although there are quite a few empirical studies that addressed prediction in ATC (e.g., Endsley, Mogford, Allendoerfer, Snyder, & Stein 1997a; Endsley, Mogford, & Stein, 1997b; Galster, Duley, Masalonis, & Parasuraman, 2001; Kimbal, 1970; Kimbal, Hofmann, & Nossaman, 1973; Metzger & Parasuraman, 2001a; Metzger & Parasuraman, 2001b; Remington, Johnston, Ruthruff, Gold, & Romera, 2000), most of these studies were concerned with controller's performance on conflict detection accuracy (i.e., the success rate of detecting conflicts) and timeliness (measured by response time); no studies have been found to address performance on the RJ and PM tasks in ATC, perhaps with an exception of Kimball (1970) and Kimball et al. (1973). The detection accuracy and the response time examined in the previous investigations seem to be the measures of the final product of conflict detection, whereas RJ and especially TTC estimation accuracy are measures of the process. When it comes to Level 3 SA, Endsley et al. (1997a) and Endsley et al. (1997b) only investigated how free flight affected controller awareness of weather impact on aircraft

and awareness of next sector for aircraft, both indicating a reduction of Level 3 SA. Parasuraman and colleagues' (e.g., Galster et al., 2001; Metzger & Parasuraman, 2001a; Metzger & Parasuraman, 2001b) mainly investigated the effects of various factors in the free flight context on controller's conflict detection accuracy and timeliness of such detection. Remington et al. (2000) examined how various factors influenced the time needed to detect a conflict and the accuracy of conflict detection, but not on the estimation accuracy of time-to-collide per se, in the free flight like vs. traditional ATC environment. However, there is abundance of literature available addressing the general paradigm of motion prediction including those investigating the RJ and PM performance, which bear some relevance to the prediction in ATC.

Factors influencing RJ performance. There are many studies that have investigated performance on RJ tasks both in 3-D egocentric and 2-D exocentric paradigms. For the 3-D egocentric stimulation simulated on a 2-D display surface, typically two or more objects were approaching the observer and the subject was to report which one would hit the observation point first. Briefly, the following result pattern, among others, emerged in experiments involving the 3-D egocentric display. It was found that as the difference in TTC increased, the percentage of correct response increased (Todd, 1980); a large but far object appeared to the subject to arrive at the viewpoint earlier than a nearer but smaller object (DeLucia, 1991).

More relevant to the ATC display is the Law et al. (1993) study, in which two small objects were moving to a contact point or points in the transverse plane in a variety of configurations, which had nine possible combinations of path types (converging, diverging, and crossing) and path relationship (parallel, oblique, and perpendicular). One of the objects would have reached its contact point first, had the display not been stopped when it had completed two thirds of its distance to the contact point. The task for the subjects was to indicate which of the two targets would reach its contact point first. When the two targets were moving at the same velocity and one of the targets was closer to the contact point, the subjects generally made the correct choices (i.e., the closer target was the first to arrive). However, when the closer target was not the first to arrive, subjects still tended to use the "closer arrives first" rule, a result showing that subjects were biased toward using the distance information relative to the speed

information present in the stimulus configurations. They also reported the following important findings:

- As the arrival-time differential (ATD) between the two objects increased, the RJ performance accuracy also increased.
- The performance accuracy decreased as the relative velocity of the two objects (expressed as the ratio of the two velocities) increased.
- Configuration had a significant effect on performance, with the parallel ones being the easiest, oblique ones more difficult, and the perpendicular ones being the most difficult.

Law et al. (1993) interpreted their results in the following way: When the velocity ratio was 1:1, it was straightforward that the object closer to the contact point would reach the contact point first based solely on the distance information, and the task became easier as the ADT increased. In the differential velocity ratio conditions, however, good performance must be based on both the distance and the velocity information, which was a more complex situation due to the multiple-dimensional nature of the task, leading to decrement in performance. The decreased performance in the differential ratio conditions indicated that the velocity information was not processed with ease or rather it was not integrated with the distance information for the distance divided by velocity strategy. According to the authors' interpretation, the effect of configuration was related to the amount of visual scanning required; that is, performance accuracy decreased with an increase in the distance between the two objects.

It is not clear whether the subjects in Law et al. (1993) used the "change in α or β " strategy described earlier in this paper (see Figure 1) when judging which object would reach the contact point first. They implied that the subjects independently assessed the TTC for the two objects and then reached the relative arrival-time decision by comparing the two TTC. It should be noted that it is not necessary to compute the TTC for that task, if the "change in α or β " or some "shortcuts" or heuristics could be used. Although Law et al. (1993) speculated that the cognitive mechanism involved in assessing arrival-time in a multiple-object situation is different from that in a single-object situation, they apparently did not consider alternative strategies potentially usable by their subjects when performing the relative arrival-time task. Used properly, these methods could simplify the relative arrival-time task, making the multiple-object task easier than the single-object task,

although Law et al. (1993) suggested that the former is more complicated than the latter.

Factors influencing PM performance. Again, as in the case of RJ studies, there are numerous studies on PM performance in the 3-D paradigm; however, since they are less relevant to the ATC display, they are not considered in this brief review (for a comprehensive review, see Hancock & Manser, 1998). The literature of the 2-D paradigm further consists of two sub-categories. One is mostly concerned with TTC estimates involving a single object moving at a constant speed along a straight line, and another is concerned with two or more objects moving in straight lines hitting a common point. A typical experiment paradigm for the former is that a target is moving from A to B along a straight line at a constant speed for some predetermined interval and then is occluded, and the subject is asked to indicate when the target is estimated to pass a third point, C. The independent variables manipulated in this paradigm include the distance or time for which the target is seen (the viewing interval: A-B) and for which it is not seen (the occluded interval: B-C), the velocity at which the target moves, and the strategies available to the subject for predicting the target future position (e.g., eye movement allowed or not allowed). There are also different dependent variables measured and analyzed in this research paradigm. Some analyzed prediction time error or prediction distance error, some looked at the error as a proportion of total time for the target to move from point of appearance to the prediction point, some examined the variability of responses under different conditions, and some computed the "subjective velocity" from subjects' responses and compared it with the actual speed of the target (see Peterken, Brown, & Bowman, 1991 for a summary). The major findings are:

- Over-estimation of TTC for fast-moving target but under-estimation for slower target.
- Slower velocity lead to greater TTC estimation errors.
- Longer occlusion time or distance resulted in longer TTC estimate.
- Occlusion distance or time had bigger effect on TTC estimation than viewing distance or time.

With respect to the TTC estimation involving multiple objects, the tasks in Kimball (1970) and Kimball et al. (1973) bore close resemblance to the conflict detection task in ATC and thus deserves a more detailed review. These might be the only studies in which absolute arrival times or TTC were

estimated involving two objects approaching to a common destination. Kimball (1970) examined how the manipulation of target velocity and angle of approach influenced the accuracy of arrival time estimation of two moving objects. The two targets simulated by two rows of lights flashing in a serial order were perceived to be moving at equal velocities. Subjects were instructed to observe the objects until they disappeared at halfway to the extrapolated intersection point and then pressed a switch to indicate when they thought the objects would intersect. Using basically the same experimental setting and task as in Kimball (1970), Kimball et al. (1973) examined how differential velocity (between the two objects), plane conditions (vertical and horizontal), and experience (air traffic controller and control group) influenced the estimation accuracy of intersection time of two targets moving on converging paths. One major difference between this study and Kimball (1970) was that the latter used two inferred moving targets approaching a common point at equal velocities on a given trial (but varied velocities across trials), whereas for the former the two targets were moving at different velocities. Therefore, the subject needed to press two switches, one for the intersection time estimations of the horizontal target and the other for the vertical target vector. The following are the major findings:

- TTC estimates were underestimated at slower velocities and overestimated for faster velocities.
- TTC estimates were more accurate at faster velocities than at slower velocities.
- TTC were more accurate at 30° than at 90° of approach angle.
- ATC experience did not improve performance.
- TTC estimates were better when the two objects were at the same speed than when they were different.

A Need for Further Research

Conflict detection is a very important part of the controller's job. Failure in this respect can result in both "misses" (the controller calls a conflict a safe separation) and "false alarms" (the controller calls a safe separation a conflict). Both of these errors obviously have serious safety consequences. The conflict detection performance in terms of TTC estimation accuracy is also meaningful in the context of concurrent task(s). Often the controller needs to attain to multiple conflict situations involving multiple aircraft and perform multiple concurrent tasks such as communications with other aircraft and

coordination with other controllers. If aircraft are predicted to be on conflict courses, then how much time can be spent on concurrent tasks before eventually returning to resolve the conflict depends on the perceived time available till the occurrence of the conflict. Therefore, given the importance of performance in TTC estimation and the lack of its research in ATC, it seems necessary and justified to fill in the gap in the literature.

At issue is how to determine experimentally how controllers perform the conflict detection task from the perspective of RJ and PM paradigms. With respect to factors influencing the RJ and PM performance, some of the candidate independent variables include but are not limited to approach angle, absolute and relative velocity, absolute and relative distance to the intersection point, absolute and relative TTC, control condition (e.g., active ATC vs. passive monitoring), and number of aircraft under control or to be monitored. Possible dependent variables can be judgment accuracy and response time for RJ, and TTC estimate accuracy and response time for PM. It is also necessary to examine the types of strategies or methods the controller would use to perform the conflict detection task. For instance, whether the controller relies on the distance-to-velocity ratio or the tau method or the CME strategy has important implications for performance of concurrent tasks. If the controller relies on the CME to project the TTC using visual modality and spatial working memory, then it would affect a visual concurrent task more than an auditory task. Or if the controller employs a distance-to-velocity ratio strategy or the tau method involving pure timing process without imposing demands on the visual/spatial resources, then the interference with a concurrent task would be the same, regardless of the modality involved in the concurrent task. DeLucia and Liddell (1998) showed that performance on PM tasks relies on CME mechanism rather than the pure timing process whereby an observer counts down time until the TTC is reached. Is this also true in ATC? Or we can ask: Under what circumstances would the controller use the CME and the distance-to-velocity ratio or the tau methods differentially?

Moreover, data of human performance without automation assistance can provide a baseline for designers to develop and improve automated conflict detection that can off-load the controller's spatial-temporal cognition. For instance, as shown above, when conflict judgments require integrating velocity with distance information, humans tend to be biased towards giving more weight to distance than to

velocity information (Law et al., 1993). Thus, automation can be employed to alleviate such bias. Many other issues can be investigated for performance with automation assistance. For instance, how do the difficulty of the RJ and PM tasks and controllers' different biases affect their use and trust of automation? We speculate that if a task is easy, they are likely to disuse automation, but in cognitively demanding conditions, they are likely to rely on automation. Also of interest is to examine the consequences of different types of automation imperfection or unreliability on conflict detection performance. Finally, we hope that future research on ATC prediction can also contribute to the basic psychology research by adding new knowledge regarding motion prediction especially where multiple objects or multiple tasks are involved.

References

- DeLucia, P. R. (1991). Pictorial and motion-based information for depth perception. *Journal of Experimental Psychology: Human Perception and Performance*, 17, 738-748.
- DeLucia, P. R., & Liddell, G. W. (1998). Cognitive motion extrapolation and cognitive clocking in prediction motion tasks. *Journal of Experimental Psychology: Human Perception and Performance*, 24, 901-914.
- Endsley, M. R. (1995). Toward a theory of situation awareness in dynamic systems. *Human Factors*, 37(1), 32-64.
- Endsley, M. R., Mogford, R. H., Allendoerfer, K. R., Snyder, M. D., & Stein, E. S. (1997a). Effect of free flight conditions on controller performance, workload, and situation awareness: A preliminary investigation of changes in locus of control using existing technology (DOT/FAA/CT-TN97/12). Federal Aviation Administration, William J. Hughs Technical Center, Atlantic City, NJ.
- Endsley, M. R., Mogford, R. H., & Stein, E. S. (1997b). Controller situation awareness in free flight. In *Proceedings of the Human Factors and Ergonomics Society 41st Annual Meeting* (pp. 4-8). Human Factors and Ergonomics Society, Santa Monica, CA.
- Galster, S. M., Duley, J. A., Masalonis, A. J., & Parasuraman, R. (2001). Air traffic controller performance and workload under mature free flight: Conflict detection and resolution of aircraft self-separation. *International Journal of Aviation Psychology*, 11(1), 71-93.
- Hancock, P. A., & Manser, M. P. (1998). Time-to-contact. In A. Feyer, & A. Williamson (Eds.), *Occupational injuries: Risk, prevention and intervention*. London, Taylor & Francis.
- Kimball, K. A. (1970). Estimation of intersection of two converging targets as a function of speed and angle of target movement. *Perceptual & Motor Skills*, 30(1), 303-310.
- Kimball, K. A., Hofmann, M. A., & Nossaman, R. O. (1973). Differential velocity and time prediction of motion. *Perceptual & Motor Skills*, 36(3), 935-945.
- Law, D. J., Pelegriano, J. W., Mitchell, S. R., Fischer, S. C., McDonald, T. P., & Hunt, E. B. (1993). Perceptual and cognitive factors governing performance in comparative arrival-time judgments. *Journal of Experimental Psychology: Human Perception and Performance*, 19(6), 1183-1199.
- Metzer, U., & Parasuraman, R. (2001a). Conflict detection aids for air traffic controllers in free flight: Effects of reliable and failure modes on performance and eye movements. In *Proceedings of the 11th International Symposium on Aviation Psychology*, Columbus, OH: The Ohio State University.
- Metzer, U., & Parasuraman, R. (2001b). The role of the air traffic control in future air traffic management: An empirical study of active control versus passive monitoring. *Human Factors*, 43(4), 519-528.
- Peterken, C., Brown, B., & Bowman, K. (1991). Predicting the future position of a moving target. *Perception*, 20, 5-16.
- Remington, R. W., Johnston, J. C., Ruthruff, E., Gold, M., & Romera, M. (2000). Visual search in complex displays: Factors affecting conflict detection by air traffic controllers. *Human Factors*, 42(3), 349-366.
- Roske-Hofstrand, R. J., & Murphy, E. D. (1998). Human information processing in air traffic control. In M. W. Smolensky, & E. S. Stein (Eds.), *Human factors in air traffic control*. San Diego, CA: Academic Press.
- Tresilian, J. R. (1991). Empirical and theoretical issues in the perception of time to contact. *Journal of Experimental Psychology: Human Perception and Performance*, 17(3), 865-876.
- Tresilian, J. R. (1995). Perceptual and cognitive processes in time-to-contact estimation: Analysis of prediction-motion and relative judgment tasks. *Perception & Psychophysics*, 57(2), 231-245.
- Wickens, C. D., Mavor, A. S., & McGee, J. P. (1997). *Flight to the future: Human factors in air traffic control*. Washington, DC: National Academy Press.