An Investigation into Conflict Resolution and Trajectory Prediction Aids for Future Air Traffic Control

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Abstract. The continuously increasing air traffic density has become a major challenge in air traffic control (ATC) due to the current ATC systems are approaching maximum capacity. To deal with the problem, an automated conflict resolution aid (CRA) and a trajectory prediction aid (TPA) have been proposed to serve as additional safety layers in the ATC systems. However, whether the proposed automation aids are worth to be applied in the current ATC workplace and could better support air traffic controllers (ATCOs) remain unknown. This study aims to investigate the effects of the proposed automations on ATCOs’ workload and situation awareness (SA). To do so, twenty-four participants were evenly divided into two groups corresponding to the presence and absence of the TPA. In each condition, participants were instructed to perform simulated ATC tasks with the double of current air traffic load under the presence and absence of the CRA. The results showed that the CRA benefits ATCOs’ workload and SA. The application of the CRA alone could benefit ATCOs while the presence of the TPA alone did not offer valuable benefits for ATCOs. Importantly, the CRA could lower the workload substantially when it was integrated with the TPA. The automation design aspect and its application in enhancing safety of future ATC are also highlighted.

Introduction

Safety of the future air traffic control (ATC) is compromised due to the continuous increase in air traffic density that is projected to be up to double in 2025 [1]. The nature of ATC tasks is tactical that includes the implementation of separation procedures for traffic collision detection and avoidance [2]. The execution of the tasks in the near future will be more challenging since current ATC systems are approaching maximum capacity and the current ATC practice may not be able to sustain the future air traffic [3].

To deal with the problem, automation has been suggested to be a practical solution. However, in the current systems, ATCOs are only provided with a conflict alerting system with a very short time allowance for the conflict resolution and have not been served with a conflict resolution automation. They still need to manually think of resolution maneuvers before the on-board traffic alert and collision avoidance system (TCAS) is activated (i.e. 45 seconds prior to the collision) while at the same time controlling other traffic aircraft [4].

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These facts clearly infer that ATCOs are in need of additional automation supports to deal with the imminent traffic growth particularly for conflict resolution and inferences of airspace information. The concepts of the conflict resolution aid (CRA) and the trajectory prediction aid (TPA) are proposed to be the additional layers for air traffic safety. However, the human-automation interaction safety critical procedures remain to be investigated before the actual implementation of the proposed automation supports. This paper presents the proposed automation concepts as well as the experimental evaluations of the concepts.

1. The concept of conflict resolution aid

The CRA is a form of automation that recommends an ATCO of a resolution maneuver. It provides a resolution advice two minutes prior to a conflict and applies the altitude-first resolver principle that suggests a vertical maneuver first over lateral and speed maneuvers due to its expediency [5] [6].

The CRA was developed with three design features. First, it implemented a “listing” style [7] that is the common presentation of the current ATC display. This is to enhance the familiarity and reduce the learning costs for new automation aids. Second, the CRA displayed an abbreviation of the established term of maneuvers in the existing ATC practice [8]. This allows for rapid understanding of the CRA advice since it complies with the present operational settings and less cognitive resources are required during the interpretation process [9]. Third, display clutter leading to costs on ATCOs’ attention must be removed. Providing two different displays for the sustenance of understanding and planning tasks [9] is a plausible design solution for the CRA application. The example of the CRA advice is shown in Figure 1. The CRA advised aircraft SQC7069 to fly heading 30 degree and aircraft VLU203 to maintain at its current state.

Figure 1. The Conflict Resolution Aid

Our recent research examining a CRA [10] provided an empirical evidence regarding the benefits of conflict resolution automation. Although the CRA is a promising concept as an additional safety layer in ATC, however, ATCOs remain in need of comprehensive inferences of airspace information to perform other ATC tasks. The inferences of airspace information are currently obtained through the complex mental computation performed by ATCOs within a limited period of time based on the information on aircraft’s data-tag. This fact together with the constantly increasing traffic would inevitably impose high mental workload on ATCOs. Hence, providing low-level
automation which focuses on the information acquisition and analysis is also deemed necessary. By doing so, the information’s inferences can be rapidly supplied to the ATCOs.

2. The concept of trajectory prediction aid

The trajectory prediction aid (TPA) is a low-level automation [11] that provides prediction of aircraft’s states. It consists of the extrapolation of some future points based on aircraft’s parameters including heading, altitude, and speed.

The design features of the TPA as shown in Figure 2 are described as follows. First, it adopts the proximity compatibility principle (PCP) [12] where a relevant task or mental operation should be provided adjacently in perceptual space through information-processing linkage. In this study, the waypoints of the aircraft’s route are displayed to increase the processing-linkage with the primary radar display. Second, the “detail on demand” principle [13] is implemented such that ATCOs are able to only allocate their cognitive resources to respective aircraft that require controlling actions. Third, providing contextual information [14] regarding all aircraft’s parameters will allow ATCOs to have the freedom in selecting relevant for any particular situation.

There are four different TPA parameters that are examined in this study including plan view, vertical view, climb/descend rate view, and speed view that show the predictions of the lateral and longitudinal positions, the altitude profiles, the climb and descend courses, and the speed profiles of an aircraft along the time axes, respectively. All the four parameters were displayed with the expected times of when an aircraft will be passing the waypoints (as indicated by the triangles) and landing on the runway (as shown by the rhombus).
3. The experiment

To further investigate into the application of the CRA and the TPA for future ATC operation, a laboratory-based experiment was conducted to examine the effects of the automations on ATCOs’ workload and situation awareness. There were six hypotheses tested in this study:

- H1. The CRA would lower ATCOs’ workload.
- H2. The CRA would enhance ATCOs’ SA.
- H3. The TPA would lower ATCOs’ workload.
- H4. The TPA would enhance ATCOs’ SA.
- H5. There would be interaction between the CRA and the TPA on ATCOs’ workload.
- H6. There would be interaction between the CRA and the TPA on ATCOs’ SA.

3.1. Methods

3.1.1. Participants

Participants in this study consisted of twenty one (21) ATCOs from the Civil Aviation Authority of Singapore (CAAS) and Singapore Air Force (SAF) and three (3) students with ATC knowledge and experience through prior ATC training. Their ages ranged from 23 to 62 years (Mean = 29.63 years, SD = 8.32 years). ATCOs’ average work experience was 4.45 years.

3.1.2. Apparatus

The NLR Air Traffic Control Research Simulator (NAR SIM) [15] that applied the standard instrument departure (SID) and standard arrival routes (STAR) of Singapore airspace was used. One ATCO’s position and two pseudo-pilot’s positions were set in the experiment. Four monitor screens were provided for the ATCO’s position to show the primary radar, the flight progress strips data that contains aircraft’s update, the CRA (Figure 1) and the TPA (Figure 2), respectively. Three monitor screens including the primary radar (Figure 3), the blipper inputs for the observation of flights’ status as well as for the maneuvering inputs, and the CRA feedback displays were placed for the pseudo-pilots’ position.

If the resolution advice given by the CRA was accepted by participants, it would be sent directly to the pseudo-pilots and the pre-programmed maneuvers would be implemented. If the advice was rejected, the pseudo-pilots would not receive resolution maneuvers from the CRA and need to wait for ATCOs’ own resolution maneuvers. For the TPA, ATCOs were able to pinpoint on respective aircraft to obtain the details about the aircraft’s current and future courses by clicking the aircraft call-sign on the display panel to activate the required information.
3.1.3. Experiment design

The factors of interest in the present study were CRA and TPA conditions. The CRA and TPA conditions were within- and between-subjects factors, respectively. Each factor consisted of two levels: presence and absence of automation. All the participants were randomly assigned to the two TPA levels. The sequence of CRA level was counterbalanced using crossover design to remove any carry-over effects.

When the CRA was available, the CRA provided correct maneuvering advice to all designated conflicts. In the absence of the CRA, participants performed the conflict resolution task manually. In both CRA levels, there was a conflict alerting system that highlighted a conflicting aircraft pair in red. Participants could perform other ATC tasks including monitoring and controlling with the aid of the TPA when it was present but they needed to perform the ATC tasks manually when it was absent.

3.1.4. Procedure

A laboratory-based experimental was performed to examine the concepts of the CRA and the TPA. A one-hour briefing and training session was provided to the participants. During the experiment, the participants were requested to perform ATC tasks that...
included controlling traffic flow and maintaining separation with the traffic density of 60 aircraft, representing double of the current air traffic load. The participants were responsible for aircraft within their controlled area and were allowed to utilize the automation aids when available. The communication between the participants and the pseudo-pilots were verbal through voice transmission. Upon receiving the instructions from ATCOs, the pseudo-pilots inputted the commands to the ATC simulator.

Participants were also instructed to respond to the real-time SA probes throughout the experiment using the Situation Present Assessment Method (SPAM). They were stimulated to respond to the SA probes if their attentional resources were available. After each experiment sessions, the participants were requested to complete the set of subjective rating for mental workload.

3.1.5. Analysis

A 2 (CRA conditions: CRA vs No CRA) x 2 (TPA conditions: TPA vs No TPA) mixed-design ANOVA was performed for the workload and situation awareness (SA) measures, respectively. Targeted t-test analysis was performed for the significant interaction found earlier in the omnibus analysis.

The workload measures included subjective and objective workload measures. NASA-TLX (ranging from 0 to 100) [16] was used to measure subjective workload. SPAM’s ready response latency and percentage of timeouts were used to measure objective mental workload [17]. The SA data were derived from SPAM’s probe response latency and percentage of correct responses [18].

3.2. Results

3.2.1. Workload

The workload rating (Table 1) was lower with the CRA than without it, F(1, 22)= 10.67, p= <0.01. Significant interaction effect between the CRA and TPA conditions on workload ratings was found, F(1, 22)= 5.58, p= 0.03. The t-test revealed that the TPA integrated with the CRA could substantially lower the workload, t(11)= 3.74, p= <0.01. Supporting the workload rating, marginally lower objective workload was observed with the CRA as indicated by the lower percentage of timeout (Table 2), F(1, 22)= 3.89, p= 0.06. There were no other significant results.

Table 1. Mean Workload Ratings (SE in parenthesis)

<table>
<thead>
<tr>
<th></th>
<th>CRA</th>
<th>No CRA</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPA</td>
<td>60.67 (3.75)</td>
<td>72.45 (2.85)</td>
</tr>
<tr>
<td>No TPA</td>
<td>71.28 (2.87)</td>
<td>73.17 (3.19)</td>
</tr>
</tbody>
</table>

Table 2. Mean Percentage of Timeouts (SE in parenthesis)

<table>
<thead>
<tr>
<th></th>
<th>CRA</th>
<th>No CRA</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPA</td>
<td>21.70% (4.78%)</td>
<td>31.48% (4.38%)</td>
</tr>
<tr>
<td>No TPA</td>
<td>26.92% (6.51%)</td>
<td>29.82% (5.37%)</td>
</tr>
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</table>

3.2.2. Situation awareness

Higher SA was found with than without the CRA, as indicated by higher correct responses to SA probes (Table 3), F(1, 22)= 10.61, p= <0.01. Consistent with the SA probe accuracy, the effect of CRA on SA probe latency (Table 4) was significant, F(1,
22)= 6.54, \( p = 0.02 \), showing higher SA with than without the CRA. The CRA and the TPA interaction on SA probe latency was significant \( F(1, 22)= 4.91, p= 0.04 \). The t-test result further showed that when the TPA was absent, the SA latency was longer when participants were not equipped with the CRA, \( t(11)= 2.59, p= 0.03 \). There were no other significant results.

Table 3. Mean Percentage of Correct Responses (SE in parenthesis)

<table>
<thead>
<tr>
<th></th>
<th>CRA</th>
<th>No CRA</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPA</td>
<td>57.41% (4.08%)</td>
<td>43.52% (4.27%)</td>
</tr>
<tr>
<td>No TPA</td>
<td>60.25% (5.86%)</td>
<td>50.54% (6.09%)</td>
</tr>
</tbody>
</table>

Table 4. Mean Probe Response Latency (SE in parenthesis)

<table>
<thead>
<tr>
<th></th>
<th>CRA</th>
<th>No CRA</th>
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<tbody>
<tr>
<td>TPA</td>
<td>11.75s (1.12s)</td>
<td>12.27s (1.38s)</td>
</tr>
<tr>
<td>No TPA</td>
<td>9.35s (0.56s)</td>
<td>16.64s (1.65s)</td>
</tr>
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</table>

Collectively, the findings are presented in the model with the hypothesized relations as shown in Figure 4.

3.3. Discussion

3.3.1. Effects of conflict resolution automation

The introduction of an additional safety layer that goes beyond alerting ATCOs of a predicted conflict to recommending a conflict resolution maneuver appeared to show positive effects on ATCOs’ workload and SA to deal with the imminent traffic growth. ATCOs showed lower workload with the aid of the CRA, supporting H1. This improvement was reflected in both subjective and objective workload measures. The CRA was found to help reduce the cost on ATCOs’ mental computation for the conflict resolution process as indicated by the lower subjective workload that is related to a task’s overall cost for a human operator [19]. This was further supported with the objective workload reduction throughout the experiment where ATCOs showed better responses to other tasks.

ATCOs’ SA was also improved with the CRA showing that H2 was upheld. The resolution maneuvering advice provided by the CRA helped ATCOs to highlight the conflict situation and the solution thus minimise the demand on processing resources [10]. Since the prediction of intervention’s consequences [20] could be processed more rapidly using the CRA, ATCOs’ SA that includes the perception, comprehension, and projection of airspace environmental status [21] was benefitted from it. Collectively, the CRA was found as a promising concept for enhancing safety of the future ATC.
3.3.2. Effects of trajectory prediction aid

The current ATC work place has not been equipped with a TPA. In the existing practice ATCOs have to rely on their mental calculation of aircraft’s future points utilizing the data of its heading, speed, and altitude that are only provided on the data-tag. In the present study, the TPA was evaluated and four aircraft’s parameters were provided including plan view, vertical view, climb/descend rate view, and speed view. Prominently, our results showed that the presence of the TPA did not benefit ATCOs’ workload and SA.

The results in this study revealed no workload reduction with the aid of the TPA, showing that H3 was not supported. However, the TPA did not compromise the workload either. These findings might be explained by the fact that ATCOs did not really rely on the TPA. ATCOs opted not to make use of the TPA particularly for routine tasks that were perceived as manageable for them. However, a higher but not significant workload rating with the TPA could be reflective of the extra workload imposed to monitor another separate TPA display [22].

Similarly, SA was neither improved nor decreased with the TPA, indicating that H4 was not upheld. This finding was particularly surprising since the TPA was expected to increase in knowledge related to the airspace inference thus increasing SA. However, associated with the workload finding, underutilization of the TPA might also explain the SA finding. ATCOs preferred to rely on their own cognitive resources to process the airspace information and to perform other tasks including responding to the SA probes. This study, however, did not find adverse effects of the TPA on SA.

Prior studies in command and control context revealed inconsistent findings about providing information for human operator during tasks performance. There were three main effects of information availability on ATCOs. First, providing information that supported tasks execution was beneficial for operator [14, 22]. Second, providing tasks-relevant information negatively affected operator’s performance [23]. Third, as what has been found in this study, contextual information did not affect tasks execution. These inconsistencies triggered a need to further investigate the application of the TPA.

3.3.3. Integration of conflict resolution and trajectory prediction aids

This study failed to show the benefits of the TPA on ATC operations when it was implemented alone. However, when it was integrated with the CRA, there was a substantial reduction on the workload, supporting H5. This finding suggested that the TPA could provide additional feedback for ATCOs on what the automation (i.e. the CRA) was doing [24]. The feedback was beneficial for ATCOs because an automation’s action is hardly understood by operator and is likely to be mediated by a display [25]. Being able to understand the CRA, whether it could do its task reliably, helped ATCOs to calibrate their dependence on the CRA, thus lowering their workload.

Furthermore, along with the substantial workload reduction, no evidence of forfeited SA was found due to the integration of the CRA and the TPA. Furthermore, ATCOs’ SA was lowest when they performed the task manually without any automation supports. In contrast with [23], this finding showed that providing task-relevant information together with the automation aid that processed similar airspace data as the provided information, helped ATCOs in maintaining their SA.

3.3.4. Practical implication and limitation
This study has positive implications for the implementation of the automation aids. First, the results revealed that the CRA benefits ATCOs’ workload and SA. This implied that a conflict resolution automation is worth investing for future ATC work place. However, the application of the TPA alone did not offer valuable benefits for ATCOs, although the integration of the TPA with the CRA could substantively reduce ATCOs’ workload. Hence, it is advisable for system designers to look for the application of either the CRA only or integrating it with the TPA for the future ATC systems.

There exist some limitations in the present study. First, the ATC simulator used in this study was a medium fidelity simulator, environmental factors such as weather were not considered during the simulation. Second, conflict resolution is often related with conflict detection. Although this issue is not addressed in this paper, misses and false alarms related to a conflict alerting system should be taken into account during the development and the application of the CRA.

Still, the design principles of the automation aids highlighted in this study offer direct implications for the safety layers in the future ATC. The findings presented in this study also outlined the worth investing ATC infrastructures.

4. Conclusion

This paper investigated some automation aids as additional safety layers that are relevant to the design for future ATC systems. Specific design features for the proposed automation aids were described. Experiment-based evaluations provide empirical evidences of the benefits and costs of the automation aids. The application of the CRA with the design features elaborated upon within this study certainly supported the users. Furthermore, the integration of the CRA and the TPA was found to markedly reduce ATCOs’ workload, thus aiding ATCOs in sustaining the imminent traffic growth.

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References


