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Effects of NextGen Concepts for Separation Assurance and Interval Management on ATCO Situation Awareness

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We examined the effects of responsibility for interval management and separation assurance on ATCo situation awareness, workload and performance. Four conditions were tested by crossing two strategies for interval management (ATCo responsible or flight deck responsible) and two strategies for separation assurance (ATCo primary or automation primary). Situation awareness and workload were assessed with an online probe technique. Workload was lowest when both functions were automated, but situation awareness for conflicts depended on the sector. Both workload and situation awareness were related to the number of ATCo-managed LOS.

An ongoing challenge for The Next Generation Air Transportation System (NextGen) is to determine the optimal function allocation strategy for air traffic management (ATM) tasks. Many proposed function allocation strategies have off-loaded ATM tasks to automation or the flight deck in order to reduce air traffic controllers' ATCos) cognitive workload because airspace capacity is often limited by the current, ground-based human-centered separation assurance system. Although greater reliance on automation and/or flight deck capabilities are expected to improve the efficiency of the NAS in NextGen, the optimal allocation strategies to achieve safe operations have yet to be determined (Kopardekar et al., 2011).

Two important air traffic management functions currently performed by ATCos are separation assurance and interval management. Separation assurance refers to ensuring legal safe distances between aircraft. Interval management is maintaining a time based interval between a lead and following aircraft to achieve a time interval (required distance) over a point in space such as the final approach fix (FAF). Both functions are currently the responsibility of air traffic control (ATC), and one or both could be allocated either to ground-based automated tools or to appropriately equipped flight decks, in order to reduce ATCo workload. Research over the past 10 years (e.g., Prevot et al., 2012) has evaluated allocation strategies for separation assurance and interval management in a series of human-in-the-loop simulations. However, these projects have focused on system outcomes (i.e., efficiency and safety) and workload, but not operator situation awareness, a known determinant of operational errors (e.g., Gronland et al., 1998). Moreover, in simulations where situation awareness was assessed, most measured the construct with custom rating scales of unknown validity, making comparisons of the changes in awareness difficult to determine.

Previous research on separation assurance has examined the impact of allocating responsibility for separation assurance either to ground-based automation or the flight deck. For example, Prevot et al. (2012) showed that ground-based automation tools could be used to increase ATC performance and reduce their workload for high-density traffic sectors. For flight-deck separation assurance, responsibility is transferred to pilots. Research has generally supported the feasibility of the concept, depending on the adequacy of support tools, both on the ground and in the air (e.g., Vu et al., 2012; Strybel et al., 2013). However, allocating responsibility for separation assurance to the flight deck does not necessarily produce equivalent reductions in the tasks performed by ATCos, because the controller is typically required to intervene in exceptional situations. In a review of flight-deck-based spacing, Zingale and Willems (2009) found that self-spacing aircraft maintained more precise spacing intervals, required less vectoring and fewer air-ground communications than aircraft that are subject to controller issue spacing (existing ground-based procedures). However, Boursier et al., 2006 found that the benefits of self-spacing depend on the percentage of aircraft engaged in self-spacing.

Recently, we evaluated the impact of alternative concepts of operations for separation assurance on pilot situation awareness, workload and performance (Strybel et al., 2013). In this simulation, responsibility for separation assurance was assigned to pilots, ATCos, or an automated, ground-based agent. Using an online probe tool (SPAM; Durso & Dattel, 2004), we showed that when pilots were responsible for separation assurance, their situation awareness increased. Strybel et al. also categorized the probe queries, and showed that the increase in pilot situation awareness was specifically higher for real or potential traffic conflicts. Moreover, the increase in awareness for traffic conflicts was not at the cost of lower awareness of other flight-relevant information such as command-communications and aircraft/airspace status. The present investigation is a follow up to Strybel et al. (2013). Here, we evaluated the impact of different concepts for separation assurance and interval management, on ATCo situation awareness, workload and performance. Using the same sectors and similar concepts of operation to those in Strybel et al., we report on preliminary data regarding the effect of different function allocation of separation assurance and interval management on ATCo situation awareness, workload and performance.

Method

Participants

Fourteen retired radar-certified ATCos (9 Center, 5 TRACON) with 11 or more years of radar experience participated. All had participated in previous simulations with the simulation software used here.

Simulation Configuration

The simulation was run using the Multi Aircraft Control System (MACS), Aeronautical Datalink and Radar Simulator (ADRS), and VoiceIP software, developed by the Airspace Operations and Flight Deck Display Laboratories at NASA Ames Research Center (e.g., Prevot et al., 2012; Johnson et al., 2005). ATCs used MACS configured as a Digital System Replacement (DSR) display with integrated Data Comm and conflict alerting. Additional tools such as conflict probes, and spacing information were provided in some concepts of operation. All aircraft were flown by pseudopilots and they also managed spacing in the Automation Primary Concept for Interval Management.

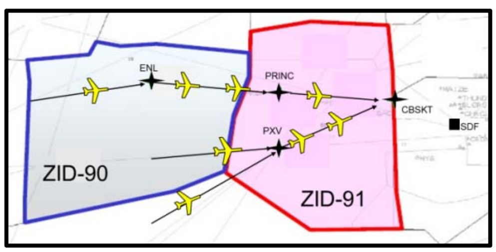

***Figure 1*. Airspace Sectors and Arrival Streams**

Scenarios

Two sectors ZID-90 and ZID-91 were simulated, as shown in Figure 1. Although sector 90 is actually a ZKC sector, it was renamed to be consistent with the simulation configuration (participants were seated next to one another in the same room). Each scenario contained arrivals to and departures from Louisville Airport (SDF), and over flights. The arrival stream consisted solely of UPS aircraft flying constant descent approaches (CDAs) on the CBSKT arrival. These aircraft entered ZID-90 from the west or southwest, and were assigned spacing lead and time en trail (105 s) upon entry. Each scenario also contained static weather cells located in the eastern portion of ZID-90. Two flight equipage types were included in each scenario, Autonomous Flight Rules (AFR) and Instrument Flight Rules (IFR). AFR flights had airborne conflict alerting and resolutions tools, and were therefore capable of self-separating. AFR flights were also permitted to deviate for weather without ATCo clearance. UPS arrivals were always on AFR flight rules. IFR flights were managed by ATCo. They were required to request weather deviations from ATCo, and had no on board conflict resolution tools.

Depending on the concept, the ATCos were responsible for separation assurance and/or interval management (spacing). In addition, the ZID-90 ATCo was responsible for handling pilot requests for weather deviations, and the ATCo in ZID-91 was responsible for managing the merging of the Pocket City (PXV) and Centralia (ENL) arrival streams out of ZID-90 to the CBSKT intersection for Louisville (SDF). Controllers in both sectors were required to respond to UPS requests for re-sequencing and spacing due to weather maneuvers. The ATCo in ZID-91 also managed SDF departures on westbound routes.

Concepts of Operation

Responsibility for resolving AFR-IFR conflicts and maintaining spacing depended on the operating concepts that are shown in Table 1. Four plausible NextGen operating concepts were evaluated, based on combinations of responsibility for separation assurance (ATC primary vs. Automation Primary) and interval management (ATC primary vs. Automation primary). For separation assurance, when ATCo was primarily responsible, all IFR-IFR and IFR-AFR conflicts were resolved by ATCo, using the trial planner and/or conflict resolution tool. When Automation was primarily responsible, AFR-AFR and IFR-AFR conflicts were resolved by the auto-resolver agent without ATCo approval. For interval management, when ATCo was primarily responsible, the UPS arrival sequence was managed by ATCo, using speed and other commands (e.g. vectoring) for spacing. When automation was primarily responsible, UPS arrival aircraft received spacing commands upon entering ZID-90, and pseudopilots engaged onboard spacing tools for interval management.

Table 1.
Concepts of operation: Separation assurance and spacing was delegated to ATCos or automation.

<table>
<tr><td colspan="2" rowspan="2"></td><th colspan="2">Responsibility for Spacing</th></tr>
<tr><td>ATC Primary</td><td>Automation/Flight Deck Primary</td></tr>
<tr><th rowspan="2">Respon-
sibility for
Separation
Assurance</th><td>ATC
Primary</td><td><u>Conflicts</u>
ATC: IFR-IFR and IFR-AFR
Automation: AFR-AFR
<u>Spacing</u>
ATC Initiates and maintains</td><td><u>Conflicts</u>
ATC: IFR-IFR and IFR-AFR
Automation: AFR-AFR
<u>Spacing</u>
Automation initiates, flight deck maintains</td></tr>
<tr><td>Auto-
mation
Primary</td><td><u>Conflicts</u>
ATC: IFR-IFR
Automation: AFR-AFR and IFR-AFR
<u>Spacing</u>
ATC Initiates and maintains</td><td><u>Conflicts</u>
TC: IFR-IFR
Automation: AFR-AFR and IFR-AFR
<u>Spacing</u>
Automation initiates, flight deck maintains</td></tr>
</table>

The DSR was equipped with advanced traffic management tools depending on operating concept. A conflict probe detected conflicts 8 minutes prior to a loss of separation (LOS) and alerted ATCo by flashing the conflicting aircraft pair in red and displaying the time to LOS next to the call signs. This tool was available for all flights. A trial planner allowed ATCos to manually create conflict-free flight plan changes for separation assurance and interval management, by clicking on the flight path, creating a new waypoint, and moving the waypoint and its corresponding flight path to a new location or clicking on the altitude in the data tag and selecting a new altitude. This tool was available for both AFR and IFR flights. An auto-resolver tool provided resolutions to conflicts when requested by ATCo. Both pilots and ATCos can request resolutions from the auto-resolver tool, depending on operating concept. The algorithm was not aware of weather, though. The auto-resolver agent detected and resolved conflicts without approval from ATCo. The auto resolver agent handled AFR-AFR conflicts under all concepts of operation, and AFR-IFR conflicts in the Automation-Primary Concept for Separation Assurance.

Situation Awareness & Workload Measurement.

To assess the impact of operating concepts on situation awareness and workload, we used the SPAM online probe technique. SPAM present SA probe questions regarding the operator's work environment while the simulation is ongoing and the displays active. Both accuracy and latency of responses to these queries are used as measures of situation awareness. Questions were delivered beginning four minutes into the scenario, and every three minutes afterwards. The queries began with a ready prompt on the probe display; ATCo responded as soon as he/she was able to respond to a query without disrupting his/her sector. If a response was not given within one minute, the ready prompt "timed out" and was removed from the screen. A new ready prompt was then presented 2 minutes later (preserving our 3-minute probe interval). Immediately after the ready prompt was responded to, a probe question was presented. These probes asked operators questions about the airspace and were formatted as either true/false or multiple choice questions. ATCo selected their answer to the question by touching the button corresponding to the answer on a touch-screen display. The probe questions were categorized based on the task information queried and whether the information was relevant to the ATCo's own sector or the sector of the adjacent ATCo.

The categories queried were conflicts, spacing status and traffic/weather. Conflict questions asked about potential conflicts [e.g., "In the next 3 minutes (20 miles), will there be any conflicts between an AFR- IFR aircraft pair if no further action is taken?"], and recent conflict resolutions, either by ATCo or by the auto-resolver (e.g., "Was the resolution to the last conflict an altitude change?"). Spacing-status questions asked about UPS arrival aircraft and their status regarding spacing [e.g., "Will any AC need re-sequencing in your sector in the next 3 minutes (20 miles). Traffic/weather questions asked about current status of aircraft in a sector such as number of AFR and IFR aircraft, altitudes and headings [e.g., "In the next 3 minutes (20 miles), from which direction will the majority of AFR aircraft enter your sector?"]. Questions also asked about weather: "How close is [AC callsign] to the nearest weather cell?"]. Workload was assessed with several measures, two of which will be reported here. We measured the latency to the ready prompt for probe queries because this latency has been shown to be related to workload. Workload ratings also were queried four times in each scenario.

Procedure

Each participant was tested over a one week period. On the first day, participants were assigned to one of the two adjacent sectors (ZID 90 or ZID 91) and were trained on the traffic flows and operating concepts. Data collection occurred on days 2-5, concluding with a debriefing session on the last day. The same pair of ATCos worked the adjacent sectors throughout the week. On each data collection day, one 50-minute scenario was run under each operating concept, with the order counterbalanced.

Results

In this paper, we present preliminary results from the simulation, focusing on sector safety, workload and situation awareness metrics. We computed the numbers of LOS for each concept that were the responsibility of ATCo (IFR-IFR LOS in automation primary, IFR-IFR + IFR-AFR LOS in ATC primary). The mean number of ATCo-responsible LOS was 1.1 (SEM=.13) in ZID-90 and 1.3 (SEM=.18) in ZID-91. Workload was measured by the ready latencies, the time between presenting the ready query and the ATCo's acceptance of it, and by the responses to the workload queries themselves. Situation Awareness was assessed in terms of response latency and response accuracy to situation awareness probe questions for each category of question.

The numbers of LOS were significantly correlated with the ready response latencies ($r = .18$, $p = .02$) such that longer response latencies were associated with greater numbers of LOS. The mean workload rating was also correlated with LOS ($r = .42$, $p < .001$), with higher workload ratings associated with more LOS. Ready latencies were also correlated with workload ratings ($r = .28$; $p < .001$). Both workload measures indicate that higher workload produced more LOS. However, both measures were also significantly correlated with probe latencies (r's =.17 and -.18 for ready latency and workload ratings, respectively). Therefore, to determine the effectiveness of situation awareness probe queries in predicting sector safety, we computed partial correlations between probe latency and probe accuracy after removing variance due to workload. Probe latency, when collapsed across information categories, was significantly and positively correlated with number of ATCo-responsible LOS ($pr = .17$, $p < .05$). Probe latencies for spacing ($pr = .16$, $p < .05$) and traffic/weather queries ($pr = .18$, $p < .05$) were also significantly correlated with LOS. Interestingly, latencies for conflict questions were not significantly related to number of LOS. Partial correlations between probe accuracy and number LOS were not significant except for accuracy on traffic/weather probes, which was marginally significant.

To determine the effect of operating concept on workload, mixed ANOVAs were run on ready latencies and workload ratings, with repeated-measures factors Separation Assurance Concept and Spacing concept, and the between-subjects factor, Sector. For ready latencies, log transformed values were used, due to violations of normality. For both ready latencies and workload ratings, significant main effects of separation-assurance concept were obtained [ready latency: $F(1,12) = 46.96$; $p < .001$; workload rating: $F(1,12) = 98.07$; $p < .001$], as well as significant interactions between separation-assurance and spacing concepts (ready latency: $F(1,12) = 8.47$; $p = .02$; workload rating: $F(1,12) = 5.22$; $p = .05$), as shown in Figure 2. For both measures, workload was lower in the automation-primary separation assurance concept than in the ATC-primary separation concept. For automation-primary separation, the lowest workload was obtained when spacing was also automated. Note, however, that when ATCo was primarily responsible for separation assurance, no difference was obtained for spacing concepts based on ready latency, and the difference between workload ratings for spacing concepts is much smaller than in the automation primary-separation concept. This suggests automating conflict resolution produces greater reductions in ATCo workload compared to when automation is responsible interval management.

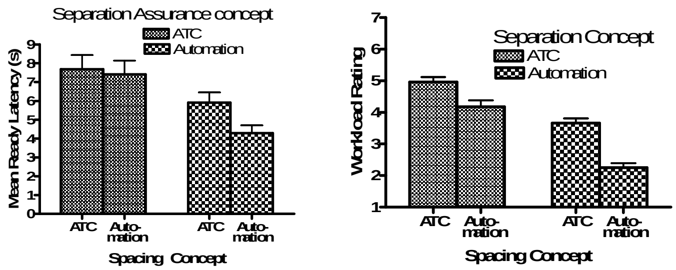

***Figure 2*. (Left) Mean ready latency and (Right) Mean Workload Rating for Each Separation and Spacing Concept.**

Situation awareness probe latencies were analyzed similarly. Probe latencies were evaluated because accuracy was not related to sector safety. Mixed ANOVAs were run on the mean probe latency for each question category: conflicts, spacing and traffic/weather. For conflict probes, a main effect of separation-assurance concept ($F(1,12) = 7.91; p = .02$) and marginal main effects of spacing concept ($p = .08$) and sector ($p = .06$) were obtained. A three-way interaction between these variables also was significant, $F(1,12) = 7.18$; $p = .02$, as shown in Figure 3.

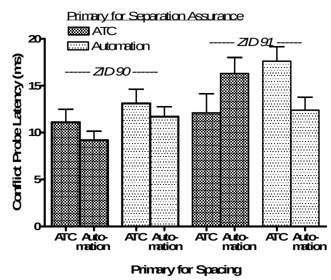

***Figure 3*. Three-way interaction between sector, separation concept and spacing concept on conflict probe latency.**

Based on conflict probe latencies, controllers in ZID-90 (M = 11.4 s, SEM = 6.3 s) were more aware of conflicts than controllers in ZID-91 (M = 14.6 s; SEM = 8.2 s). In ZID-90, latencies for the ATC-primary separation assurance concept were lower overall than for the automation-primary concept, suggesting that ATCos had higher conflict awareness when they were responsible for detecting and resolving most of the conflicts. Moreover, greater awareness of conflicts was observed in ZID-90 with automation-managed spacing regardless of separation-assurance concept. In fact, the highest conflict awareness occurred for ATC-managed separation and automation-managed spacing. In ZID-91 a different picture emerged. First, the simple effect of separation assurance concept was nonsignficant, because when automation was primary for separation assurance, greater awareness of conflicts was found with automation-primary spacing, similar to ZID-90. However, when ATC was responsible for separation assurance, greater awareness was observed when ATC was primary for spacing. In effect, in ZID-91, greater conflict awareness occurred when both functions were either automated or controlled by ATCo.

Discussion

Our measures of workload and situation awareness were related to the number of ATCo-managed LOS. When automation was primary for separation assurance, only IFR-IFR LOS was the responsibility of the controller. When ATCo was primary, IFR-IFR and IFR-AFR LOS were the responsibility of the controller. Although the number of LOS obtained in the present simulation are higher than what is typically expected, it is important to keep in mind that this level of LOS is not surprising given the high traffic density we used in the simulation. We found that both workload and situation awareness metrics were related to the number of LOS.

The results from the workload data are straightforward: workload was lowest when automation was responsible for both spacing and separation assurance. However, when only one function was automated, automated responsibility for separation assurance produced lower workload than automated responsibility for spacing. This was not surprising considering that ATCos had to monitor more aircraft, including those AFR aircraft that might be a threat to an IFR aircraft, when they were primarily responsible for separation assurance. For the ATCo-primary spacing conditions, the ATCos were responsible for fewer aircraft.

However, the cost of lower workload with automated separation assurance and spacing may lie in lower ATCo situation awareness, with awareness for some information more affected than others. Awareness of conflicts was highest when ATCo was primary for separation assurance and automation primary for spacing. This may be due to the lower workload experienced for the automation-primary spacing condition when ATCo was responsible for separation. This finding was limited to controllers in ZID-90, in which most of the spacing was initiated. In ZID-91, awareness of conflicts was highest (probe latencies lowest) when both concepts were either automated or managed by ATCo. Assuming that fewer spacing clearances were required because most AC were sufficiently lined up in the upstream sector, the ZID-91 ATCo may have been more aware when both concepts were consistent.

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