CONTROLLER PERFORMANCE, WORKLOAD AND ATTENTION ALLOCATION IN DISTRIBUTED AIR-GROUND TRAFFIC MANAGEMENT: EFFECTS OF MIXED EQUIPAGE AND DECISION SUPPORT

Ulla Metzger, Ericka Rovira, and Raja Parasuraman
The Catholic University of America
Washington, D. C., USA

The introduction of the concept of Distributed Air-Ground Traffic Management (DAG-TM; NASA, 1999) will lead to the situation where some aircraft will be fully equipped and able to participate in Free Flight (FF), while others will be unequipped and still require full control by air traffic control (ATC). The present study investigated how such mixed equipage affects air traffic controller (ATCo) performance and mental workload in a simulation of FF conditions with different proportions of managed and unmanaged aircraft. The effects of automated decision support were also examined. Sixteen ATCos performed a simulated ATC task with or without decision support and with varying proportions of managed aircraft (70%, 50%, or 30%). Dependent variables included the accuracy and response time in detecting potential conflicts, accepting and handing off aircraft. Some evidence of negative consequences for ATCo performance of a mix of managed and unmanaged traffic was obtained. However, it was also found that automation could compensate for these effects. Additionally, mental workload was reduced only slightly with high proportions of unmanaged suggesting that aircraft providing their own separation assurance might not reduce ATCo workload as much as expected.

Introduction

The introduction of concepts such as Distributed Air-Ground Traffic Management (DAG-TM; NASA, 1999) or Free Flight (FF; RTCA, 1995) will lead to the situation where some aircraft will be fully equipped and able to participate in Free Flight (FF), while others will be unequipped and therefore still require full control by air traffic control (ATC). This situation of mixed equipage raises several issues. How will air traffic controllers (ATCos) know which aircraft participate in FF and which do not? Will ATCos be able to successfully intervene in cases when self-separations between unmanaged aircraft fail? How does the requirement to monitor these unmanaged aircraft affect ATCo mental workload? Even though the rationale for concepts such as FF or DAG-TM is the assumption that a high proportion of unmanaged aircraft would reduce ATCo workload, little research has been done to address these issues.

Corker, Fleming, and Lane (1999) studied the effects of different proportions of mixed equipage (100% managed; 80% managed-20% unmanaged; 20% managed-80% unmanaged) on ATCo detection of airborne self-separations and workload under FF conditions. With 20% of the aircraft unmanaged, workload was comparable to managed conditions. With 80% of the aircraft unmanaged, however, workload significantly increased compared to 80% and 100% managed conditions. The authors speculated that the increase in workload was due to the high demand for monitoring and suggested that some form of decision aiding (e.g. presentation of pilot intent information or pilot conformance monitoring) to support ATCos was required.

The present study examined the effects of a decision-support tool (DST) under different proportions of managed and unmanaged traffic (mixed equipage) on ATCo performance, mental workload, and attention allocation in a simulation of FF conditions. The major questions of interest were whether ATCos would be able to detect conflicts between unmanaged aircraft and whether automation would positively affect ATCo performance under these conditions.

Method

Participants

Sixteen active full-performance level ATCos (two females) from the Washington air route traffic control center and area terminal radar control facilities served as paid participants. Their ages ranged from 33 to 54 years (M=40.13; SD=5.84), and their ATC experience from 10 to 22 years (M=15.81; SD=3.78).

Apparatus

A PC-based medium-fidelity ATC simulator (Masalonis, Le, Klinge, Galster, Duley, Hancock, Hilburn, & Parasuraman, 1997) was used to simulate a generic airspace. The simulation consisted of a radar or primary visual display (PVD) and a data link display which were presented on two adjacent monitors. A trackball was used as input device for both monitors. The PVD of the 50-mile radius sector consisted of aircraft targets, data blocks, jet routes and waypoints. In all conditions, ATCos were required to monitor traffic for potential conflicts and report them by selecting the aircraft involved and clicking on a conflict button. A loss of separation or conflict was defined as two aircraft coming within 5nm horizontally and 1000 feet vertically of each other at all flight levels. Potential conflicts could result in an actual *conflict* or a *self-separation*. A conflict was defined as two aircraft heading towards each other at the same altitude and loosing separation. A self-separation existed when one of two aircraft on a conflict course made an evasive maneuver to avoid the loss of separation either by changing speed or altitude. While self-separations represented instances of successful airborne separation that would not require any ATCo action in the real world, conflicts were instances in which airborne separation failed and the ATCo would be expected to intervene under FF conditions.

In addition to detecting conflicts, the ATCos' task was to accept aircraft into the sector and hand them off to the next sector as they were leaving. This was mostly a communication task performed on the data link display on the monitor adjacent to the radar. The ATCos' embedded secondary task was to monitor the progress of aircraft on the electronic flight progress strips on the data link display. The strips included all waypoints that a flight crossed on its way through the sector as well as altitude information. ATCos were required to check off each waypoint on the flight strip as soon as the aircraft passed it on the radar display. Traffic density was relatively high (about 17 aircraft) in all scenarios. In order to create a set of six very similar scenarios, the sector and traffic patterns were rotated. Waypoints and flights were changed for each scenario. Subjective ratings of mental workload were obtained on the NASA Task Load Index (TLX), subjective ratings of trust and self-confidence to perform without the automation were obtained on a 100-level rating scale. An Applied Science Labs (ASL) 5000 eye-head tracking system was used to obtain eye point-of-gaze data at a sampling rate of 60 Hz.

Design

Independent variables. A 2 (manual versus automated) x 3 (proportion managed versus unmanaged aircraft) within-subject design was chosen. In the manual condition, ATCos performed all tasks with no automated decision support. In the automated conditions, ATCos were supported with a conflict detection aid in the form of red bubbles around aircraft projected to be in conflict with a six-minute look-ahead time. In addition, a DST indicated which managed aircraft could be assigned a conflict-free direct route to a destination further along the flight plan. The DST allowed the ATCo to choose this direct route (instead of following the filed flight plan route that might not be the most time- or fuel-efficient) and, if a conflict was present, resolve that conflict by assigning a direct route. In the automated conditions, the automation tools (e.g. conflict detection aid and DST) were available both together, whereas in the manual conditions neither was available to support the controller. Traffic mix was either 70% managed versus 30% unmanaged, 30% managed versus 70% unmanaged, and 50% managed versus 50% unmanaged. Each of the resulting six scenarios contained three self-separations between unmanaged aircraft and two conflicts. One of the conflicts occurred between two managed aircraft and one between two unmanaged aircraft.

Dependent variables. The detection of conflicts and self-separations served as a primary task performance measure. If ATCos did not indicate the detection of a conflict before the loss of separation or the beginning of an evasive maneuver, a miss was recorded. Advance notification time was defined as the time the loss of separation occurred (for conflicts) or would have occurred had the aircraft not self-separated (for self-separations) minus the time the ATCo reported the detection of a potential conflict. The greater the value, the earlier the detection took place and the better the conflict detection performance. Timeliness and accuracy in the communication to accept and hand-off aircraft were also obtained.

Secondary task performance was assessed by the task of monitoring the progress of aircraft through the sector. Dependent variables were the percentage of successfully updated waypoints as well as response times (i.e. the interval between the time an aircraft crossed a waypoint on the radar display and the time the ATCo acknowledged that the aircraft passed the waypoint by clicking on the corresponding waypoint on the electronic flight progress strip). However, this task was only relevant for the manual condition. By sending aircraft directly to a destination under automated conditions the aircraft bypassed some of the waypoints that otherwise had to be updated.

Subjective ratings of mental workload were obtained after all scenarios by averaging the ratings on the six TLX sub-scales. Additionally, subjective ratings of trust in the automation and self-confidence to perform without the automation were obtained after the automated conditions on a scale ranging from 0 to 100.

Eye point-of-gaze data was analyzed by extracting the number and duration of fixations on four areas of interest: the radar display, the flight progress strips, the communication area, and the DST. Fixations were defined as the mean x- and y-coordinates measured over a minimum of 100 ms during which the eye did not move more than 1 degree vertically and horizontally. The ASL analysis program allows matching fixation to the four areas of interest and determining how often and how long the eye fixated on each area.

Procedure

ATCos received instructions and performed several practice trials before performing in the six 25-minute scenarios. The order of scenarios was counterbalanced. For each participant, eye movements were recorded in four out of six scenarios. The scenarios were chosen so that an equal number of recordings per scenario was obtained.

Results

Primary task performance

Detection of two conflicts (managed vs. unmanaged). A 2 (automation condition) x 3(traffic mix) x 2 (conflict between managed or unmanaged aircraft) repeated measures ANOVA was calculated. A significant effect of traffic mix on detection rates was found, $F(2, 30) = 4.42$, $p < .05$. The higher the proportion of managed traffic, the higher the detection rates ranging from 92.19% (SE = 3.38), 82.81% (SE = 4.75) to 75.00% (SE = 5.46) for proportions of 70%, 50%, and 30% managed aircraft, respectively.

A non-significant trend for a higher detection rate for the conflict between unmanaged aircraft (M = 87.50%, SE = 3.39) than for the conflict between managed aircraft (M = 79.17%, SE = 4.17) was found, $F(1, 15) = 2.50$, $p = .13$. A significant interaction for automation condition and conflict is shown in Figure 1, $F(1, 15) = 5.28$, $p < .05$. While there was no difference in the detection between the managed and the unmanaged aircraft in conflict under manual conditions, considerably fewer ATCos detected the conflict between managed aircraft than between unmanaged aircraft under automated conditions.

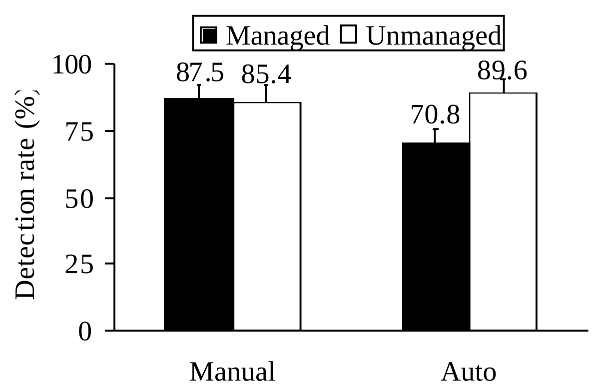

Figure 1: Detection rates for conflicts as a function of automation condition and conflict type

Advance notification times for two conflicts (managed vs. unmanaged). Missing cells due to missed self-separations were replaced by the mean of the respective scenario. Under automated conditions ATCos detected conflicts significantly earlier (M = 350.95 s; SE = 8.20) than under manual conditions (M = 270.41 s, SE = 14.54), $F(1, 15) = 19.60$, $p < .001$. The effect of traffic mix failed to reach significance, $F(2, 30) = 2.14$, $p = .14$. The earliest notification occurred in the condition with 30% managed aircraft (M = 324.57 s; SE = 14.67), the latest in the condition with 50% managed traffic (M = 298.10 s; SE = 16.50) and the condition with 70% managed aircraft in between (M = 309.38 s SE = 14.65).

ATCos detected the conflict between managed aircraft significantly earlier (M = 374.05 s; SE = 8.64) than the conflict between unmanaged aircraft (M = 247.31 s; SE = 12.40), $F(1, 15) = 97.59$, $p < .0001$. Figure 2 shows the significant interaction between automation condition and managed or unmanaged conflict, $F(1, 15) = 20.14$, $p < .001$. While the detection of the conflict between managed aircraft improved only slightly with automation, the detection of the conflict between unmanaged traffic benefited significantly from the automation aid (greater notification time).

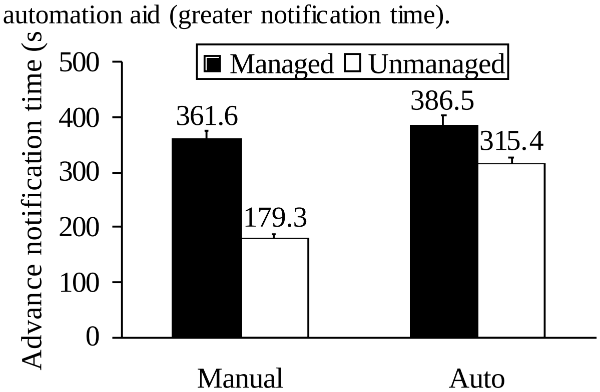

Figure 2: Advance notification times as a function of automation condition and conflict type

Detection of self-separations (all between unmanaged aircraft). The detection of the first self-separation was not analyzed because it appeared right after the start of the scenario and was missed only two times overall. The main purpose of the first self-separation was for the ATCos to build trust in the automated detection aid (in the automated conditions). For the detection of the remaining two self-separations, higher detection rates were found under automated (M = 96.88%; SE = 1.77) than under manual conditions (M = 63.54%; SE = 5.31), $F(1, 15) = 25.26$, $p < .001$. There were no effects of traffic mix, $F(2, 30) < 1$, or the interaction, $F(2, 30) < 1$.

Advance notification times for self-separations. ATCos detected self-separations earlier under manual (M = 138.15 s; SE = 6.92) than under automated conditions (M = 104.78 s , SE = 8.09), F(1, 15) = 16.14, p = .001. ATCos detected self-separations earlier with lower proportions of managed aircraft, F(2, 30) = 5.34, p = .01. They detected self-separations 112.29 s (SE = 8.99), 113.75 s (SE = 9.89), and 138.36 s (SE = 9.60) before the potential conflict would have occurred (had the aircraft not self-separated) for proportions of 70%, 50%, and 30% of managed aircraft, respectively. The interaction between automation condition and traffic mix was non-significant, F(2, 30) = 1.20, p > .05.

Efficiency. The time aircraft spend in a sector can be considered a measure of efficiency. The more ATCos use the DST, the shorter the time indicating more efficient ATC service – the goal of future ATC concepts and DST. A significant effect of automation on time in sector was found, F(1, 15) = 173.20, p < .0001. Under automated conditions, aircraft spent shorter times in the sector (M = 720.12 s; SE = 1.06) than under manual conditions, (M = 732.27 s; SE = .47). Efficiency was also affected by traffic mix, F(2, 30) = 140.57, p < .0001. The higher the proportion of managed traffic (that could not benefit from direct routes), the longer the time aircraft spent in the sector. Aircraft spent on average 732.22 s (SE = .89), 724.51s (SE = 1.30), and 721.85 s (SE = 1.50) in the sector for proportions of 70%, 50%, and 30% managed aircraft, respectively. In addition, a significant interaction was found, F(2, 30) = 10.12, p < .001. As figure 3 displays, the benefit of the DST becomes larger with higher proportions of unmanaged and lower proportions of managed traffic.

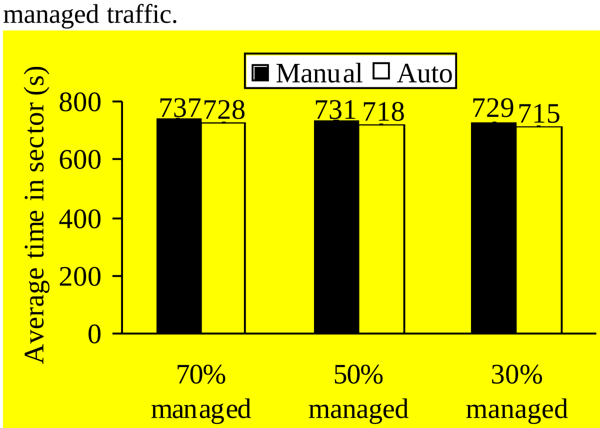

Figure 3: Average time in sector as a function of automation condition and traffix mix

Communication task. Overall, ATCos missed accepting very few aircraft (M = .87%; SE = .13) and there was no effect of traffic mix, F(2, 30) < 1, or automation condition, F(1, 15) < 1. However, there was an effect of traffic mix on the time it took ATCos to accept aircraft into the sector, F(2, 30) = 3.73, p < .05. The higher the proportion of managed traffic, the longer it took ATCos to accept aircraft into the sector. It took ATCos 39.15 s (SE = 4.21), 35.90 s (SE = 3.87), and 33.22 s (SE = 3.20) to accept aircraft when the proportions of managed aircraft were 70%, 50%, and 30%, respectively.

There was a trend for a higher percentage of successful hand-offs in the condition where 70% of the aircraft were managed (M = 71.47%; SE = 4.31). The lowest percentage of successful hand-offs was found in the condition where 30% of the aircraft were managed (M = 65.79%; SE = 4.13) with 50 % managed traffic in between (M = 70.42%; SE = 3.66), F(2, 28) = 2.18, p = .13. ATCos missed to handoff more aircraft under manual (M = 5.46; SE = .92) than under automated conditions (M = 3.36; SE = .72), F(1, 14) = 3.53, p = .08.

Secondary task performance. The effect of traffic mix was analyzed for the manual condition. It took ATCos on average 114.23 s (SE = 10.79) to update the waypoints under manual conditions. There was no significant effect of traffic mix on response times, F(2, 30) < 1, or successful updates, F(2, 30) < 1.

Subjective Ratings. ATCos rated their mental workload higher under manual (M = 60.43; SE = 2.44) than under automated conditions (M = 52.92; SE = 2.09), F(1, 15) = 5.94, p < .05. There was no significant effect of traffic mix on subjective workload ratings, F(2, 30) = 1.16, p > .05. The interaction between automation condition and traffic mix was also non-significant, F(2, 30) = 1.17, p > .05. ATCos rated their trust in the automation moderate (M = 68.13; SE = 3.94), but still higher than their self-confidence to perform without the automation (M = 61.15; SE = 3.90). Traffic mix had no significant effects on ratings of trust, F(2, 30) < 1, or self-confidence, F(2, 30), < 1.

Number of fixations. The number of fixations differed significantly between area of interest, F(3, 45) = 917.17, p < .0001. ATCos made the most fixations on the radar (M = 2365.87; SE = 41.96), followed by the communication area (M = 604.31; SE = 16.46), the flight strips (M = 186.19; SE = 12.84) and the DST area (M = 39.96; SE = 3.91).

Figure 4 displays a trend for an interaction between automation condition and traffic mix, F(2, 30) = 2.54, p < .1. There was very little variation in the number of fixations under automated conditions. Under manual conditions, however, ATCos made the most fixations in the condition with equal amounts of managed and unmanaged traffic. Figure 5 shows a trend for an interaction between automation condition and area of interest, F(3, 45) = 2.20, p = .1. Under automated conditions, ATCos made more fixations on the DST area than under manual conditions. This was done at the expense of fixations on the flight strips and, to a lesser extent, on the radar.

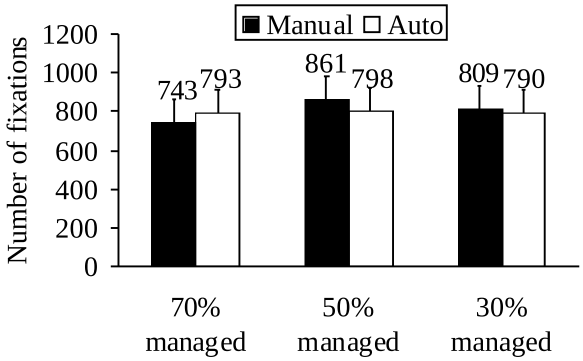

Figure 4: Number of fixations as a function of automation condition and traffic mix

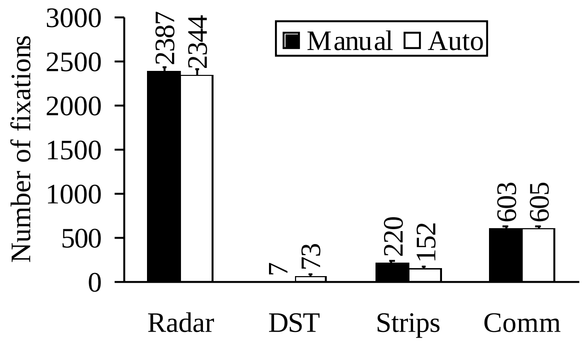

Figure 5: Number of fixations as a function of automation condition and area of interest

Duration of fixations. The duration of fixations varied significantly by area of interest, $F(3, 45) = 1204.02$, $p < .0001$. The longest durations were found on the radar (M = 892.92 ms; SE = 17.46), followed by the communication area (M = 206.30 ms; SE = 5.74), the flight strips (M = 57.23 ms; SE = 3.95) and the DST area (M = 13.56 ms; SE = 1.29). A significant interaction between area of interest and traffic mix is displayed in figure 6, $F(6, 90) = 2.36$, $p < .05$, showing that ATCos made the longest fixations on the flight strips and the communication areas in the condition with 50% managed traffic. This was at the expense of fixations on the radar where the shortest fixations were in the condition with 50% managed traffic.

A trend for an interaction between automation condition and area of interest was found, $F(3, 45) = 2.05$, $p = .12$. Figure 7 shows that in the manual conditions ATCos fixated longer on the radar, flight strips, and communication areas than in the automated conditions. Average fixation durations on the DST were longer under automated than under manual conditions.

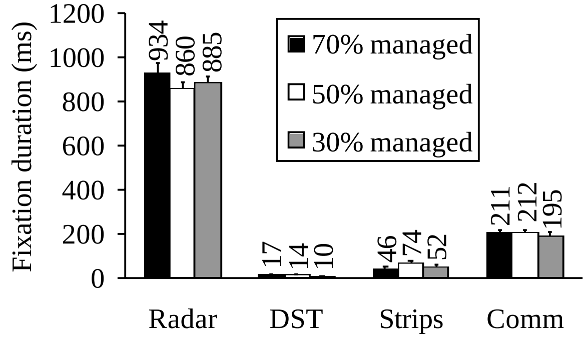

Figure 6: Fixation duration as a function of traffic mix and area of interest

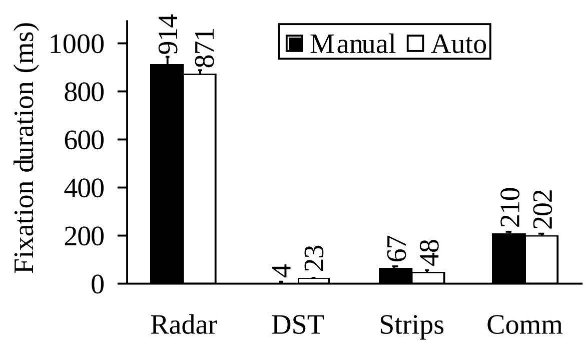

Figure 7: Fixation duration as a function of automation condition and area of interest

Discussion

One of the most important questions of this study was how the mix of traffic would affect the detection of potential conflicts and, in particular, how well ATCos would be able to detect conflicts between unmanaged aircraft with and without the support of automation. Overall, it was found that the higher the proportion of managed aircraft, the higher the detection rates; conversely the higher the proportion of unmanaged aircraft, the lower the detection rates for conflicts. The conflict between managed aircraft was detected earlier than the conflict between unmanaged aircraft. With the aid of automation ATCos detected conflicts earlier than under manual conditions. The reduced performance in the detection of conflicts between unmanaged compared to managed aircraft improved significantly in terms of notification times when ATCos had automation support available. These findings demonstrate that (a) performance in the detection of conflicts between unmanaged aircraft is reduced under conditions of mixed equipage, but (b) can be improved with automated decision support.

It is unclear, however, why there was a trend, albeit non-significant, for detection rates for unmanaged aircraft in conflict to be higher than for managed aircraft in conflict. It is also surprising that the detection of conflicts between managed aircraft was reduced under automated conditions. This unexpected trend can be partially explained by the eye movement data. ATCos made more and longer fixations to the DST during automated conditions than during manual conditions. There were similar findings when ATCos had a higher proportion of managed aircraft in the automated condition. This pattern suggests that the DST drew attention away from the radar to the DST.

The higher detection rates, but later notification under automated conditions for self-separation could reflect a speed-accuracy trade-off. Why ATCos detected self-separations between unmanaged aircraft earlier with lower proportions of managed traffic and higher proportions of unmanaged traffic is unclear. Perhaps ATCos have difficulties in managing their attention allocation between the managed and unmanaged aircraft. Due to the high proportion of unmanaged aircraft their attention might tend to shift to the unmanaged rather than the managed aircraft where it would be expected.

A pattern of better performance in terms of successful hand-offs and worse performance in response times for accepting aircraft in the condition with 70% managed aircraft compared to lower proportions of managed traffic was found. The slower response time during acceptance could simply reflect the increased housekeeping duties (i.e. communicate, update waypoints) with higher proportions of managed traffic and a workload management strategy. The better hand-off performance with 70% managed compared to lower proportions of managed traffic could be due to the fact that ATCos became negligent to monitor the aircraft and determine when they had to be handed off in the condition with a high proportion of unmanaged aircraft. In the condition with 70% of the aircraft managed they might have been more vigilant and therefore performed better.

Another issue was whether mental workload would decrease (because unmanaged aircraft do not require as much attention as managed aircraft) or increase (because unmanaged aircraft impose a high monitoring load due to the uncertainty about their intent; Corker et al., 1999) with the proportion of unmanaged aircraft. Contrary to the results by Corker et al. (1999) subjective ratings did not indicate a reduction in mental workload with increasing proportions of unmanaged aircraft. Also, there was no effect of traffic mix on secondary task performance under manual conditions. Perhaps the lack of a workload reduction with high proportions of unmanaged traffic is due to the high monitoring load imposed by these aircraft as suggested by Corker et al. (1999). Hence, aircraft providing their own navigation and separation assurance might not reduce ATCo workload as much as expected. Although ATCos perform fewer routine tasks for unmanaged aircraft (e.g. keeping track of fewer waypoints), the high uncertainty about aircraft intent could lead to high monitoring requirements and cancel any potential workload benefit. Automation reduced subjective ratings of workload. However, this could be confounded with the fact that fewer waypoints had to be updated in the automated condition because aircraft could be sent to their destination directly.

Analysis of the eye data showed that overall ATCos made the most fixations to the radar followed by communication, flight strips, and DST areas respectively. While in the automated conditions there was little variation in the number of fixations, in the manual conditions ATCos made the most fixations when the proportion of managed and unmanaged traffic was equal, perhaps reflecting that without automation the equal proportions of managed and unmanaged traffic required more attention in distinguishing between the aircraft. Lastly, additional fixations and longer fixations to the DST in the automated conditions support the ATCos' use of the DST and the resulting improved efficiency (time aircraft spends in sector) in ATC service.

These results indicate that a mix of managed and unmanaged traffic can have negative consequences for ATCo performance unless well-designed decision support is provided. In case of a conflict between unmanaged aircraft, ATCos might not be able to detect it efficiently. Automation however, can compensate for these effects and lead to improved ATCo performance. Unless efficient automation support tools are provided, ATCos might not be able to safely handle a mix of traffic (Parasuraman, Hilburn, & Hoekstra, 2001). Hence future research needs to address which information ATCos require to distinguish between managed and unmanaged aircraft, and how such information should be presented to the ATCos.

Acknowledgements

This research was supported in part by grant No. NAG-2-1096 from NASA Ames Research Center, Moffett Field, CA (Dr. K. Corker/Dr. R. Mogford) and in part by grant No. GSRP ORG 364230 from NASA Langley Research Center (David Wing). We would like to thank all ATCos who participated in the experiment.

References

Corker, K., Fleming, K., & Lane, J. (1999). Measuring controller reactions to free flight in a complex transition sector. Journal of ATC, 4, 9-16.

Masalonis, A. J., Le, M. A., Klinge, J. C., Galster, S. M., Duley, J. A., Hancock, P. A., Hilburn, B. G., & Parasuraman, R. (1997). Air traffic control workstation mock-up for Free Flight experimentation: Lab development and capabilities. *Proceedings of the Human Factors and Ergonomics Society 41st Annual Meeting* (pp. 1379). Santa Monica, CA: HFES.

NASA (1999). *Concept definition for distributed air/ground traffic management (DAG-TM)*. Version 1.0. Advanced Air Transport Technologies (AATT) Project. Aviation System Capacity (ASC) Program. Available: http://www.asc.nasa.gov/aatt/dag.html

Parasuraman, R., Hilburn, B., & Hoekstra, J. (2001). Free Flight. In W. Karwowski (Ed.) *International Encyclopedia of Ergonomics. and Human Factors.* (pp. 1005-1008). New York: Taylor and Francis.

RTCA (1995). Report of the RTCA Board of Director's Select Committee on Free Flight. Washington, D.C.: RTCA.