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Shifts in air traffic controllers' situation awareness during high altitude mixed equipage operations

Sarah Gregg, Lynne Martin, Jeffrey Homola, Paul Lee, Joey Mercer, Connie Brasil, Christopher Cabrall, and Hwasoo Lee
San Jose State University Foundation at NASA Ames Research Center
Moffett Field, CA

Abstract. Studies of future airspace design often predict that automated tools will be available to assist the controller and sometimes complete tasks independently of controller intervention. How this redistribution of functions will change the role of the controller needs to be considered, as does its impact on the controller's awareness of aircraft movement in their sector. In a study of high altitude operations in future airspace where aircraft were equipped with different levels of data communications capabilities, it was found that about half of the participants positively attributed the contribution of the automation as assisting their own level of situation awareness (SA) – and hence perceived themselves as being in a better position in terms of SA under more automated / equipped conditions. Whereas the other half of the participants, who did not consider the automation to assist their situation awareness, perceived themselves as having higher SA under conditions that were closer to the current day. With increased reliance on automation and higher expected traffic volume in the future, controllers will need to rethink what constitutes as their SA since they will no longer be able to have a complete awareness of their airspace as they do now. Insights into new SA strategies that can factor automation's contribution and integrate it into controllers' awareness could be helpful in future training and tool design.

INTRODUCTION

Air Traffic Controllers' expertise lies in their ability to understand the performance and speed of aircraft, their current positions, their future positions, and how these will interact in the given airspace of a sector. A key component of an air traffic controller's expertise lies in developing "situation awareness" (SA), which has been described as "the perception of elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future" (Endsley, 1988, p792). Because SA is an important component of a controller's duties, developing and maintaining SA forms a large part of a controller's workload (Durso, Hackworth, Truitt, Crutchfield, Nikolic & Manning, 1999). To keep the demand on a controller's cognitive capabilities within bounds, the number of aircraft allowed into many en route sectors is limited. This limitation is intended to hold controllers' workload at manageable levels (and reduce the risk of error). However, the Next Generation Air Transportation System (NextGen) predicts that traffic demand will increase for the next 15 years (JPDO, 2011, p2-25). This could raise controller workload to unmanageable levels and render situation awareness (as defined above) impossible to achieve if controllers continued to use current methods. Because controllers will no longer be able to maintain an awareness of all the aircraft within their sector, the development of automated tools and revisions to airspace design are being explored.

In July 2011, a human-in-the-loop simulation researching flow corridors was conducted in the Airspace Operations Laboratory (AOL) at the NASA Ames Research Center (Homola et al., 2012). This simulation examined the feasibility and benefits of creating highly structured routes, or "corridors", flown by aircraft with common avionics equipage at common speeds to increase the sector capacity. The corridors aimed to decrease controller workload by creating a structured and predictable flow of aircraft with matched speeds and headings, allowing the aircraft to be appropriately spaced, thus reducing the complexity of the traffic.

In addition to the corridor structure, the provision of data communications (Data Comm) aimed to decrease controller workload by allowing 4D trajectory amendments to be uploaded as well as transfer of communications (ToC). The proportion of aircraft equipped with Data Communication was varied across the study conditions. Also, controllers were provided with some automated separation tools, such as conflict alerts, to flag particular aircraft that required action.

Since the study aimed to present traffic demand that was impossible to manually control, it was predicted that controllers would have to rely on the automated tools to gain SA of particular aircraft that required an action, instead of maintaining an ongoing awareness of every aircraft in the sector. This suggests that controller strategies for SA may have to change as traffic increases and automated tools and airspace design develop. The implication of this argument is that the criteria for which elements/ aircraft controllers have to be "aware" will change. The focus of this paper is to explore whether and how controllers' SA strategies are shifting and the implications for future air traffic operations

METHOD

2.1 The Simulation: Airspace, corridor structure, traffic levels

The study was run in the AOL at the NASA Ames Research Center using Multi Aircraft Control System (MACS) software (Prevot, 2002). MACS provides an environment for rapid prototyping, human-in-the-loop air traffic simulations, and evaluation of current and future air/ground operations.

The test airspace was super-high en route sectors (Flight Levels (FL) 330 and above) in the Cleveland Center (ZOB) as shown in Figure 1; see Homola, et al. (2012) for more details about the study. Each corridor was a one-way route travelling both to and from the New York Metro area at two separate altitudes (FL340 and FL360). Each corridor had two parallel lanes to accommodate aircraft flying at two different speeds. The corridors were considered a part of each sector and were managed by the respective sector controllers. All aircraft were equipped with flight management systems (FMS) with Automatic Dependent Surveillance-Broadcast (ADS-B) and area navigation (RNAV) capabilities. The aircraft in each scenario varied by equipage, defined by whether or not they had Data Comm capabilities (uplinking route, altitude, speed, and transfer of communications). Aircraft unequipped with Data Comm did not have these capabilities and required voice communication from the controllers.

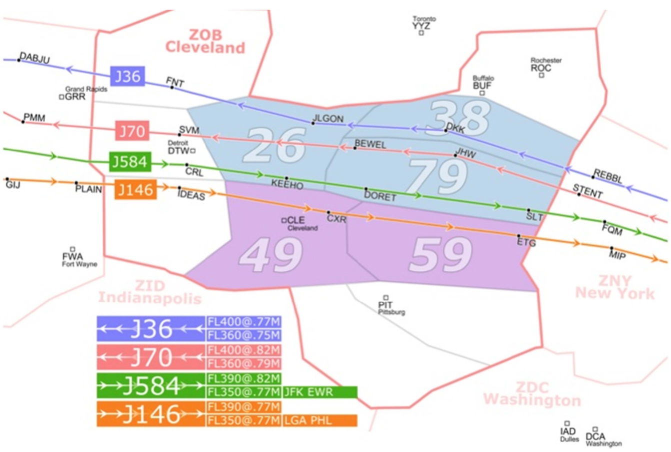

Figure 1: Test airspace and its surrounding area.

Traffic density was based on a previous complexity calculation, where the maximum capacity of a ZOB sector was set to around 22 aircraft (Prevot & Lee, 2011). Using this as a capacity threshold, traffic was scheduled through the test airspace at two traffic densities (High and Max). High traffic conditions were built to have a 30 minute period (during a 1 hour run) where the traffic count in any one sector was up to seven aircraft above the threshold and Max traffic conditions were built to have 30 minute periods where the traffic count in any one sector was up to a dozen aircraft above the threshold. Traffic was not simultaneously high in all sectors as this would have caused saturation and stifled the problem. If the traffic exceeded the threshold of the sector load graphs, a traffic flow manager and area supervisors coordinated to reroute a limited number of aircraft out of the congested sectors. This occurred often in the Max Traffic but rarely in the High Traffic conditions.

Three different mixes of equipped and unequipped aircraft were tested with two corridor structures: (1) only equipped aircraft within corridors (Equipped-in-Corridors, EiC); (2) a mix of both equipped and unequipped aircraft within the corridors (Mixed-in-Corridors, MiC); (3) a 50/50 mix of equipped and unequipped traffic with no corridors (Mixed-No-Corridors, MNC); and (4) only unequipped aircraft within corridors (Unequipped-in-Corridors, UiC). Non-corridor traffic in each sector consisted of a 50/50 mix of Data Comm equipped and non-Data Comm (unequipped) aircraft for all conditions. The EiC condition had about 66% Data Comm equipped traffic per sector across the scenarios and the UiC condition was the mirror image with about 66% of its traffic being unequipped. In both conditions, two thirds of this traffic was in the corridors, reducing the complexity of the flows in the sectors. In the MiC condition, although corridors were present they contained an equal mix of equipped and unequipped aircraft, increasing the complexity of sector management somewhat. The MNC condition had the same traffic mix as the MiC condition, i.e., 50/50, but no corridor route structures organizing the predominant flows.

2.2 Automated tools

At the sector level, conflict detection automation was active and resolution support was available. Voice communications were also available at all times between controllers and pilots. For Data Comm equipped aircraft, clearances were sent either via Data Comm and loaded into the FMS, or via voice where the pilot manually performed the required actions. Handoffs and ToC for Data Comm equipped aircraft were automated and did not require controller involvement. For unequipped aircraft with no Data Comm capability, clearances were verbal only and were typically followed by controller actions to update the system accordingly. Handoff initiations were automated but acceptance and ToC were performed manually by the controller.

2.3 Controller tasks, participants, and data collection

Thirteen recently retired air traffic controllers from Oakland Center (ZOA) participated in this simulation. Three controllers staffed supervisory positions, five staffed radar (R-side) positions, three staffed on-demand data (D-side) positions, and two staffed supporting confederate “ghost” controller positions. All but one of the controllers had participated in previous studies in the AOL and were familiar with the simulation platform. General aviation students and pilots ran seven simulation-pilot stations to control the simulated aircraft.

Participants took part in 1.5 days of formal training to ensure their familiarity with the concept, tools, and procedures. Following training, 32 one-hour runs alternated High and Max Traffic conditions, with the four equipage/corridor conditions counterbalanced throughout.

Participants were asked to manage their traffic as they normally would with no special procedures for the aircraft in the corridors. They were asked to give priority to traffic in the corridors (when present) and to provide service for equipage (i.e., favor equipped aircraft to maintain their user-preferred trajectory), workload and safety permitting.

Data were recorded for each run through the MACS’ data collection logs, including losses of separation (LoS) between aircraft. Screen and voice recordings were also collected for each run at each station. Following each run, the participants completed an online questionnaire that included rating the three dimensions of the Situation Awareness Rating Scale (SART, Selcon & Taylor, 1990). A final questionnaire was presented to the participants at the conclusion of the data collection that covered topics of interest at a higher level and included a series of questions about the controllers' perceived SA.

RESULTS AND DISCUSSION

In the post-study questionnaire, controllers were asked about the complexity, sector load, and their situation awareness under the study conditions. In the responses where they ranked the conditions, controllers agreed that the Mixed-No-Corridors condition was the most complex and they could handle the least traffic in these runs (Table 1), whereas the Equipped-in-Corridors condition was the least complex and they could handle the most traffic in these runs. These reports are consistent with the intended differences in complexity between conditions. However, when participants were asked

Table 1. Frequency of participants' ranking of the complexity of the study conditions, with most popular rank- position highlighted

Condition	EiC	MiC	UiC	MNC
Least complex	6	1		1
Rank 2	1	4	2	1
Rank 3		3	5	
Most complex	1		1	6

to rank the study conditions in terms of the SA they had of their sector, although half of the participants ranked their awareness highest in the EiC condition, (as predicted in our study hypotheses), the other half of the controllers said their awareness was highest in the Mixed-No-Corridors condition (Table 2). The remainder of this paper explores other

Table 2. Frequency of participants' ranking of the study conditions for when their SA was highest, with most popular rank-position highlighted [Group 1=light grey, Group 2=dark grey]

Condition	EiC	MiC	UiC	MNC
Highest SA	3	1		4
Rank 2	1	4	3	
Rank 3		3	5	
Lowest SA	4			4

subjective and objective measures that were taken during the study to try to account for why these controllers felt their SA was higher with fewer tools and less structure and ascertain whether these controllers' different approaches to creating and maintaining their SA resulted in consequential differences in behavior.

3.1 Survey responses

A post-study question explored the impacts that traffic equipage had on the way participants characterized their SA. While some controllers just said their awareness was good or bad, half characterized their SA by describing the degree of monitoring they did and whether they kept the data block expanded for the aircraft. In general, controllers kept the data blocks expanded for unequipped aircraft and collapsed for equipped aircraft. For those controllers who had ranked their SA as highest in the EiC condition (Group 1), collapsed data blocks were construed positively because this reduced controllers' monitoring load. For those controllers who had ranked their SA as highest in the MNC condition (Group 2), collapsed data blocks were construed negatively because they felt they were not actively monitoring these aircraft and so, in their opinion, they did not have awareness of this traffic. Both groups of controllers agreed they relied more heavily on the automation with respect to equipped aircraft. It is interesting that the dichotomy between these two groups is not in their behaviors – most manipulated their data blocks in similar ways – but in how they perceived a greater proportion of equipped aircraft and a greater need to rely on the automation to both flag and solve problems as either freeing (Group 1), or reducing their general awareness (Group 2). This observation then suggests that some of our participants may have embraced working with the assistance of automation more readily than others, which may be related to their perception of their own awareness. To further explore participants' perceptions of their SA, participants' SART ratings were compared.

3.2 SART

The three dimensions of the SART (Selcon & Taylor, 1990) asked participants to rate the information available in the situation ("understanding"), how much mental demand the situation placed on their attention ("demand") and how much spare mental capacity they felt they had available to deal with the situation ("capacity"). Participants rated these elements from 1 "very low" to 7 "very high". The rankings were sorted into the two groups identified above (by the participant's general view of when their SA was highest) and by the position the participant worked (R-side, D-side), then by condition (EiC, MiC, MNC, UiC) for each traffic level (Max & High). The mean rating for each of the 32 runs was obtained to allow descriptive comparison. D-sides were excluded from the following analyses because they did not always participate in a given run. Additionally, R-side ratings are discussed only under Max Traffic conditions (a total of 16 one-hour runs) due to space limitations, although the data during High Traffic conditions yielded similar findings.

Figure 2 and Figure 3 show mean SART ratings for the two groups of controllers. Each cluster of bars represents a dimension, and within each cluster the four bars represent each study condition under the Max Traffic scenarios. Group 2 (Figure 2) reported the lowest demand and the highest capacity, on average, in the EiC condition (left bars for each dimension). These mean ratings increased for demand and decreased for capacity as a function of equipage levels to the UiC condition where they reported the highest demand and the lowest capacity on average (right bars for each dimension).

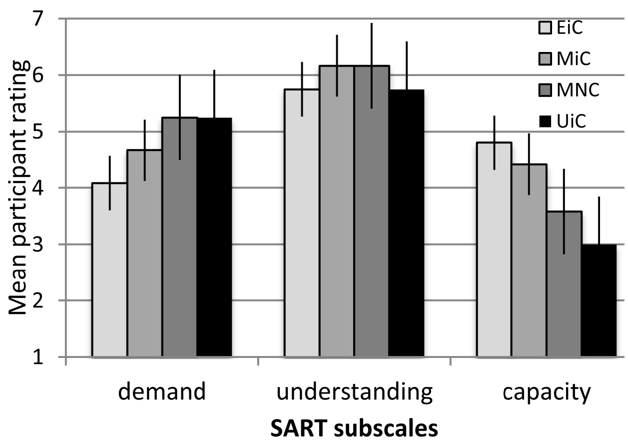

Figure 2: Mean situation awareness ratings of 3 SART subscales under four corridor conditions and under maximum traffic loads for R-side controllers in Group 2.

Group 2 reported similar mean levels of situation understanding (range 5.75-6.12 across the four conditions).

These ratings combine, using Taylor and Selcons' method where SA is calculated by Understanding – (Demand - Capacity), to give Group 2 the highest mean SART score in the UiC condition (M=8) and the lowest mean SART score in the Equipped-in-Corridors condition (M=5), a pattern consistent with their descriptions of their SA in the questionnaires. It should be noted that all of these mean SART scores could be categorized as "reasonable SA" since the SART metric is scaled from 13 "very high" to -5 "very low" when a 7 point rating is used for the subscales.

Group 1 participants reported demand, understanding, and capacity ratings that, as means, have a similar pattern to Group 2 (Figure 3). However, their ratings differ in some small but meaningful ways. Although their mean situation understanding varied little (from 6.25-6.75 across the conditions), the mean ratings were a little higher in the conditions with a 66%/33% equipage mix compared to Figure 2 (EiC, UiC). These differences across the eight rating categories were significant (F(7,8) = 21.86, p=.003) when tested using a Friedman two-way ANOVA; and secondary pairwise comparisons using Wilcoxon Signed Rank tests supported the differences between Group 1 and Group 2's EiC ratings (Z=2.23, p=.026) and their UiC ratings (Z=2.33, p=.02).

Similar to Group 2, Group 1 reported feeling the highest demand on average in the MNC condition and the lowest demand in the EiC condition, but their mean ratings were a scale point higher, indicating that they felt higher demand in general regardless of the condition. There was a significant difference between the ratings of Group 1 compared to Group 2 (Z=3.82, p=.000), but not within Group 1 or within Group 2's ratings. Capacity ratings formed the reverse pattern, as Group 1's capacity ratings were significantly lower than Group 2's (Z=-2.36, p=.018), but there were no differences within the groups.

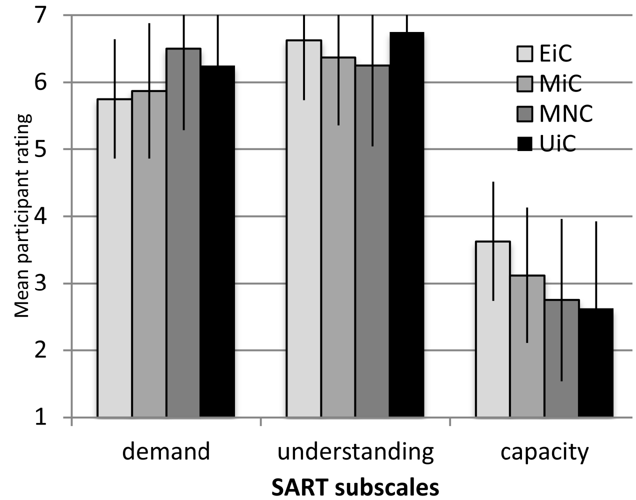

Figure 3: Mean situation awareness ratings of 3 SART subscales under four corridor conditions and under maximum traffic loads for R-side controllers in Group 1.

Thus, Group 1 felt the traffic situation was more demanding and that they had less capacity than Group 2. This could be due to specific differences in the sectors that these controllers worked but may also reflect their approach to developing and maintaining SA when working with automation. Group 1's ratings combined to give participants the highest mean SART score in the UiC condition (M=10.37) and the lowest mean SART score in the EiC condition (M=8.75) (Figure 4). This pattern was not consistent with Group 1's post hoc descriptions of when their SA was highest (see Section 3.1) but was not a significant difference. However, their SART

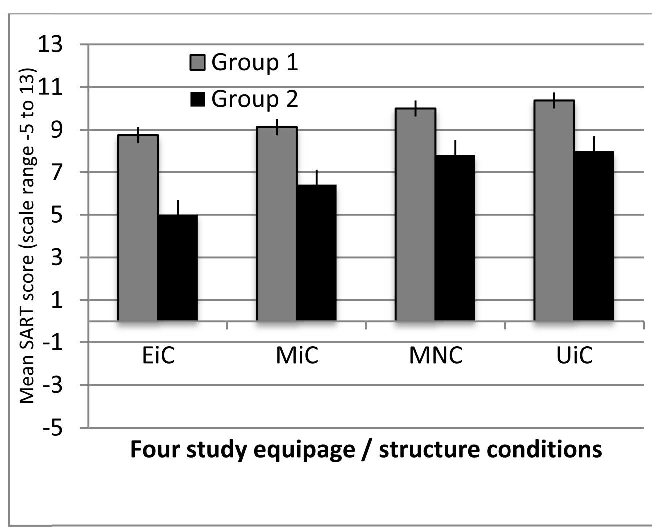

Figure 4: Mean SART scores under four corridor conditions and maximum traffic loads for two groups of R-side controllers who defined their SA strategy differently.

scores for all four conditions were greater than those for Group 2, i.e., Group 1 had a higher SART score in every study condition ($F(7,8) = 22.55$, $p=.002$), which may be an indication that their approach – using the automation to take some SA tasks and redefining their SA strategy – enabled them to maintain a higher level of SA overall in terms of their own definition.

3.3 Losses of Separation

Another way to look at participant awareness was to review events, such as losses of separation (LoS), which possess large SA components both in their identification and in the process of developing solutions. LoS were recorded in MACS data logs whenever two aircraft came within 5 nautical miles laterally and 1000 feet vertically of each other. Separation violations were not counted if they occurred within the first five minutes of a given run or lasted less than twelve consecutive seconds (the duration of an update cycle of the en route radar displays in today's system). Additionally, both aircraft involved in a separation violation had to be owned by one of the test sectors, and could not have been a result of a ghost controller or simulation-pilot deviation. Over the course of the 32 runs, only two LoS occurred. The first LoS occurred during a MNC condition and the second during a UiC condition, both under High Traffic levels. Interestingly, both separation violations occurred in Group 2 controllers' sectors.

As each LoS occurred, the controller was either at the beginning or the end of a peak period in terms of traffic count, and was working on normal housekeeping tasks, such as making and taking handoffs. It is possible that with the higher number of aircraft, the demand imposed by housekeeping tasks, especially if the controller was trying to maintain a broad level of SA comparable to a current day strategy, would be large enough that the controller was fully occupied and did not have the attention resources for general monitoring at that time. It should be noted, however, that there are too few observations for conclusions to be drawn from these LoS findings, and further research is needed.

CONCLUSION

In this study of high altitude en route redesign, one of the key feasibility questions was whether the controllers could maintain sufficient situation awareness in highly automated environments. If the number of aircraft per sector increases, and automation developed to assist the controller is installed, controllers' displays may be configured to reduce workload but at the cost of controller actions that help to maintain SA. Our interest was to explore whether or not the controllers would shift their SA strategies in simulations of future airspace concepts to utilize the automation.

In this study, participants' SART ratings and qualitative responses to SA questions (including some not reported here) gave an unexpectedly consistent picture of our participants' approaches to how they focused their efforts to generate and maintain awareness. It seems that one group (Group 2) was trying to construct and maintain their SA as they have always done, whereas another group, Group 1, may have been adapting their preexisting SA strategies to take advantage of the automated resolutions and the task reduction that accompanied equipped aircraft. Thus, there seemed to be two approaches: half of our participants favored increased automation capabilities for directing their attention to where they needed high situation awareness, whereas the other half favored maintaining their own SA building routines without the contributions of automation. Whilst there was no statistical difference in controller performance between the two groups, there was some indication that trying to maintain a general SA (as current day controllers do) became harder with the increased traffic as both LoS events occurred in sectors where participants described their SA as better under conditions similar to the current day (Group 2) (see Homola, et al., 2012 for workload assessments). As air traffic increases in the future, controllers will need to develop and use SA building strategies that incorporate the assistance of automation. Studies such as the one reported above will contribute to an understanding of how controllers interact with automation and gain awareness that can be used in training SA strategies and in the design of automated tools.

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