2007

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COLLABORATION TECHNOLOGIES AND THE SUPERVISORY CONTROL OF UCAVS IN TACTICAL C2: EFFECTS ON PERFORMANCE AND WORKLOAD

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The present study was an initial attempt to characterize team performance, workload, and situational awareness associated with two types of UCAV control schemes coupled with several collaboration technologies. Six people participated in a simulated suppression of enemy air defense (SEAD) mission, which required cooperation between all participants in order to meet mission objectives. UCAVs were controlled by UCAV operators and supervised by air battle managers (ABMs) or controlled directly by ABMs. Participants could communicate verbally, through instant messages, and on some trials, using a virtual whiteboard. Results of the experiment indicated that team performance was negatively impacted by direct UCAV control and communication using the virtual whiteboard. Overall, these results suggest that direct UCAV control may have subtle, yet substantial, negative impact on several aspects of team performance and that efficient use of collaboration technologies in temporally demanding environments may require operators to first develop effective communication strategies.

Introduction

The E-3 Sentry, an Airborne Warning and Control System (AWACS) aircraft, is highly regarded as the premier air battle management command and control (C2) platform and provides the U.S. military with the surveillance, command, control, and communications needed for effective battle management, and its capabilities continue to evolve.

Concurrently with the AWACS's continued development, considerable military interest has been expressed in the development of unmanned combat aerial vehicles (UCAVs) for use in suppression of enemy air defense (SEAD) missions (Worch et al., 1996). SEAD missions require air assets to suppress or destroy enemy air defenses, usually by compelling anti-aircraft or surface-to-air missile (SAM) sites to activate their radars, and subsequently firing anti-radiation missiles at the activated sites (e.g., Li et al., 2002). Currently, SEAD missions are some of the most dangerous and demanding that a pilot can undertake (Nelson & Bolia, 2006), making them ideal for UCAVs.

UCAV Control

At present, air battle managers (ABMs) aboard AWACS are responsible for the tactical control of air interdiction and deep strike, both of which involve the coordination of fighter cover, strike assets, airborne refueling, and SEAD (e.g., Kopp, 2002). Within the framework of current and near-term concepts of operations, the inclusion of UCAV assets in SEAD missions will require ABMs to expand their duties to include management of teams of UCAV operators. However, this command structure could place increased workload demands on ABMs as they must dynamically communicate with and coordinate SEAD mission assets in order to meet mission objectives.

Alternatively, some analysts have advocated direct control of UCAVs by ABMs, thereby expanding the ABMs' responsibilities while simultaneously eliminating the need for additional personnel (e.g., Kopp, 2002). It has been suggested that direct ABM control of UCAVs may yield several tactical benefits including reduced deployment costs, reduced sensor-to-shooter time, and more seamless integration of manned and unmanned SEAD assets (Nelson & Bolia, 2006).

However, direct UCAV control by ABMs has been criticized on several grounds, including the possibility that direct control may simply change ABMs' workload from communication with UCAV operators to workload associated with monitoring UCAV operations, a change which may engender unintended consequences (Parasuraman & Riley, 1997). Specifically, this shift brings into question the impact of direct control on ABMs' mental workload, situational awareness (SA), and decision and mission effectiveness, and what, if any, countermeasures may be devised to address these issues (see Nelson & Bolia., 2006 for a comprehensive review).

Collaboration Technologies

Recent trends in military acquisition have emphasized the desire to introduce collaboration technologies into C2 environments (Kaufman, 2005). Proponents of network-centric operations have argued that these technologies might engender increased SA and task flexibility (Alberts & Hayes, 2003). These technologies could potentially mitigate ABMs' expected workload increases associated with UCAV operations.

However, research investigating the influence of collaboration technologies on team performance has generally indicated they exert a substantial *negative* effect on team performance. For example, Bordia (1997) concluded that teams restricted to collaboration technologies made poorer decisions, measured both objectively (e.g., meeting task goals) and subjectively (e.g., quality of solutions), and took more time to reach a decision. Moreover, team members experienced less satisfaction with team processes.

Conversely, recent research conducted by Funke, Galster, Nelson, and Dukes (2006) found no adverse effects of one collaboration technology, instant messaging (IM), on team performance in a simulated C2 task. Participants restricted to IM communication performed at a rate comparable to participants who were not so restricted.

The current study represents an initial, exploratory attempt to characterize team performance, workload, and SA associated with several UCAV control schemes and collaboration technologies.

Method

Participants

Six people (5 men, 1 woman) between the ages of 19 and 36 (M = 23.5, SE = 2.59) served as paid participants in this study. Participants all had prior experience with the DDD interface used in this study; however, none of them had prior experience with the current scenario. Participants were required to have normal or corrected-to-normal vision and normal color vision.

Experimental Design

A 2 × 2 within-subjects design was employed, with two UCAV-control conditions (direct, supervisory) combined factorially with two levels of collaboration condition (standard, whiteboard) and six levels of team position (ABM-sweep, ABM-UCAV, sweep-operator-1, sweep-operator-2, bomber-operator, UCAV-operator).

UCAV control and team position were block factors, and collaboration condition was randomized within each block. Participants completed two trials in each condition, for a total of 48 trials.

Measures of individual and team performance included the number of enemy targets destroyed, the number of team assets killed, and frequency and type of team communication. Subjective measures included the NASA Task Load Index (TLX; Hart & Staveland, 1988) and the 3-D Situational Awareness Rating Technique (SART; Taylor, 1990).

Apparatus

The simulated environment utilized was Aptima, Inc.'s Distributed Dynamic Decision-making (DDD) simulation, a team-in-the-loop simulated environment which has previously been employed in a variety of military and civilian research projects. The simulation required 16 networked PCs communicating under TCP/IP protocol. Each workstation was equipped with a keyboard, mouse, and two monitors. The DDD display was projected on a 17-inch ViewSonic VP720b LCD monitor and the Windows operating environment was projected on an 18-inch NEC MultiSync 1800 LCD monitor. A Synergy KM switch, model 1.3.1, allowed participants to interact with desktop objects on each monitor with a single mouse. Verbal communication, participant behavior, and screen captures were recorded using Nuance SDK (version 8.5) and MORAE (version 1.1.1) software.

The whiteboard collaboration condition utilized the Dynamic Real-time Animated Whiteboard (DRAW) application. The DRAW tool is an experimental, virtual whiteboard which enables users to annotate and send images of a battle-space to each other.

Simulation

The DDD was used to create a simulated SEAD mission scenario, in which participants were tasked with following a specified flight path, conveyed through a tactical display, in order to meet SEAD mission goals. The objective of each mission trial was to destroy as many enemy targets as possible while simultaneously protecting team assets.

The ABMs coordinated the actions of other team members in order to meet objectives. ABM-sweep directed the movement and target acquisition of both sweep-operators. The responsibilities of ABM-UCAV were contingent upon the UCAV-control condition of each trial. In the supervisory UCAV-control condition, ABM-UCAV directed the bomber- and the UCAV-operator. In the direct UCAV-control condition, the role of UCAV-operator was subsumed by ABM-UCAV, who then manually controlled UCAV assets in addition to directing the bomber-operator.

At the start of each mission trial, each operator controlled four assets of the same type. Each asset had a limited amount of ammunition and fuel. As these resources were depleted, assets would have to return to a 'home-base' to be restocked and refueled. Assets that ran out of ammunition were unable to attack, and assets that ran out of fuel 'died' and were removed from the simulation. Initial fuel levels of each asset were randomized between three to nine minutes of fuel to ensure each asset would require refueling. After refueling, fighter and bomber assets were equipped with seven minutes of fuel, and UCAV assets were equipped with nine minutes of fuel.

Additional assets of each type were available to operators from home-base to replace units that were killed or that needed restocking or refueling. Participants were instructed to maintain four assets of the appropriate type in the simulation at all times, and to launch additional assets from home-base to replace assets as needed. However, operators had to receive orders from their respective ABM to launch from or return assets to home-base.

To further simulate the role of ABMs in a combat situation, the tactical displays of UCAV-, bomber-, and sweep-operators conveyed limited information concerning enemy units within the simulated battle-space. The ABMs' displays, on the other hand, were not limited in this fashion, giving them a more complete understanding of the battle-space.

The capabilities and assets of each operator were specialized for their role within the SEAD mission. Specifically, the UCAV-operator was responsible for eliminating enemy surface-to-air-missile (SAM) sites. The bomber-operator was responsible for destroying strategic enemy ground targets. The two sweep-operators were collectively responsible for protecting assets from enemy fighter aircraft. Each unique role was designed such that each position's contributions could not be replicated by those of another position (e.g., a UCAV could destroy a SAM site, but a bomber could not). This division of simulated capabilities resulted in a situation in which success or failure of each mission trial was dependent upon the contributions of all team members.

Each ten-minute mission trial featured 36 SAM sites and 24 bridges randomly distributed around the flight path. Thirty-six enemy MiGs were programmed to enter the scenario at random intervals during each mission trial. SAM sites and bridges were stationary, while MiGs were mobile. Both SAMs and MiGs could 'kill' team assets, while bridges were passive entities which did not threaten team assets.

Procedure

Training. Participants received 42 hours of instruction and practice with the SEAD mission task, distributed across ten days. Participants first completed a computer-based training module, which instructed them on the nature and responsibilities of the task as well as familiarized them with the controls of the DDD interface. Participants then received more role specific instruction for each team position, and direct training with the DDD interface.

Participants also received instruction on the use of the radio communication equipment, instant messaging, and virtual whiteboard employed in the experiment. To discourage verbal communication through other means, a recording of pink noise was played in the lab during each mission trial. Participants also received training on completion of the NASA-TLX and 3-D SART.

Participants practiced until they could demonstrate proficiency at all positions. Although each position differed slightly, in general, this entailed achieving 75% of mission goals in a single trial. Immediately following practice trials, participants were debriefed about their performance and about aspects of their performance that needed to be addressed in order to demonstrate proficiency.

Experimental data collection. The experimental data collection phase of the experiment began immediately following completion of training. Data collection required 15 hours, distributed over 3 days. Each participant was randomly assigned to an order of team positions. Participants then completed eight trials in that team configuration, before rotating to their next team position. This process was duplicated six times, until each participant had completed eight trials in each team position. During each eight-trial block, participants completed four trials in each collaboration condition.

After completing all experimental trials, participants completed a debriefing questionnaire. This measure was designed to elicit participants' impressions of the SEAD mission, the DDD software, and the collaboration tools employed in the experiment.

Results

To examine potential differences in team response to the experimentally manipulated factors, an ABM-team factor with two levels (sweep-team, UCAV-team) was conceived. Sweep-team consisted of ABM-sweep and the two sweep operators. UCAV-team consisted of ABM-UCAV and the bomber- and UCAV-operators.

Team Performance

Enemy targets destroyed. To determine the effects of the experimental manipulations on the number of enemy targets destroyed, the percentage of ABM-team targets destroyed in each trial was computed. The data for this factor were tested for statistical significance by means of a 2 (control condition) × 2 (collaboration technology) × 2 (ABM-team) repeated measures analysis of variance (ANOVA). A statistically significant main effect of ABM-team was detected, F (1,5) = 22.19, p<.05. The mean percentage of ABM-team targets destroyed was significantly higher for the ABM-sweep team (M = 99.36, SE = .23) compared to the ABM-UCAV team (M = 82.78, SE = 3.58).

Assets killed. The effects of the experimentally manipulated factors on the numbers of each type of team asset killed (fighters, bombers, UCAVs) were tested by separate 2 (control condition) × 2 (collaboration technology) repeated measures ANOVAs. For the number of fighter assets killed, all sources of variance in the analysis were not significant (p > .05). However, a trend within the data suggested that more fighter assets were killed in the direct control condition (M = 2.71, SE = .20) compared to supervisory control condition (M = 1.92, SE = .27) (p < .10).

For the number of bomber assets killed, a statistically significant main effect of collaboration condition was detected, F (1, 5) = 12.00, p < .05. Fewer bomber assets were killed in the standard collaboration condition (M = .71, SE = .14) compared to DRAW condition (M = 1.21, SE = .17).

For the number of UCAV assets killed, a statistically significant UCAV-control × collaboration condition interaction was detected, F (1, 5) = 7.49, p < .05. As is illustrated in Figure 1, the greatest number of UCAV losses occurred in the direct UCAV-control DRAW collaboration condition.

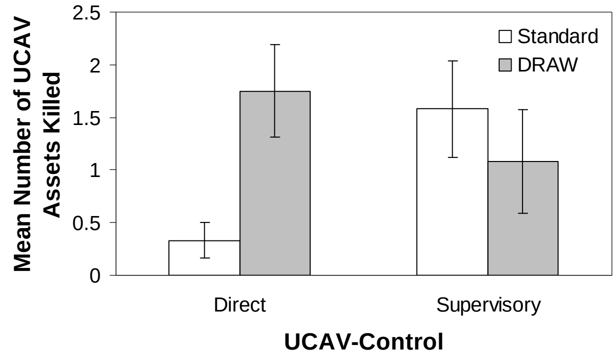

Figure 1. Mean number of UCAV assets killed as a function of UCAV-control and collaboration conditions. Error bars are standard errors.

To further explore the UCAV-control × collaboration interaction, separate repeated measures ANOVAs were calculated in which collaboration condition was analyzed for each UCAV-control condition. For direct control, a statistically significant main effect of collaboration condition was detected (F [1, 5] = 14.31, p < .05), but no such difference was detected for the supervisory control condition (p > .05). Fewer UCAV assets were killed under direct UCAV control in the standard collaboration condition (M = .33, SE = .17) compared to the DRAW condition (M = 1.75, SE = .44).

Base launches. Both ABM-teams were responsible for launching new assets from home-base to replace assets that were killed or refueling. Therefore, the optimal number of base launches in any trial was equal to the number of assets returned to home base plus the number of assets killed. However, participants did not always perfectly adhere to these instructions. An index of launch inefficiency (LI) can be calculated as LI = observed launches – optimal launches. This index was calculated for each condition across trials and compared by means of a 2 (control condition) × 2 (collaboration technology) × 2 (ABM-team) repeated measures ANOVA. For launch inefficiency, a statistically significant main effect of ABM-team (F [1, 5] = 44.93, p < .05) and a statistically significant UCAV-control × ABM-team interaction (F [1, 5] = 7.79, p < .05) were detected. As is illustrated in Figure 2, the sweep-team maintained fewer assets in the simulation than the UCAV-team.

To further explore the UCAV-control × ABM-team interaction, separate repeated measures ANOVAs were calculated in which UCAV-control condition was analyzed for each ABM-team. For the sweep-team, a statistically significant main effect of UCAV-control condition was detected (F [1, 5] = 13.89, p < .05), but no such difference was detected for the UCAV-team (p > .05). The sweep-team maintained a greater number of assets in the simulation in the direct control condition (M = -2.17, SE = .51) compared to the supervisory control condition (M = -2.79, SE = .48).

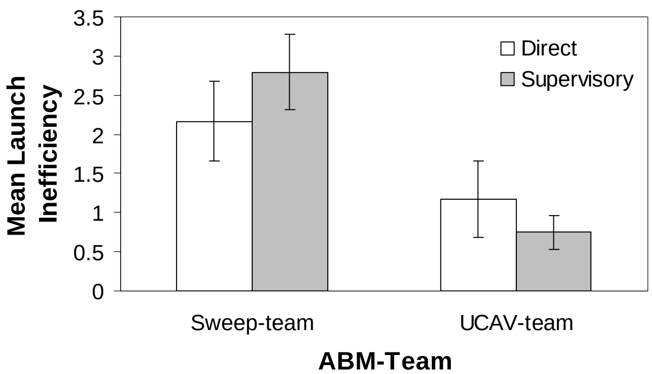

Figure 2. Mean launch inefficiency (absolute values) as a function of UCAV-control and ABM-team conditions. Error bars are standard errors.

Subjective Workload and Situational Awareness

Workload. A 2 (control condition) × 2 (collaboration technology) × 6 (TLX subscale) repeated measures ANOVA indicated a statistically significant main effect of TLX subscale, F (1.29, 6.45) = 14.60, p < .05. In this analysis, Box's epsilon was employed to correct for violations of the sphericity assumption (Maxwell & Delaney, 2004). A subsequent post hoc Tukey's HSD of TLX subscale revealed no significant differences between subscales (all p > .05). Participants' ratings of workload were not influenced by the experimentally manipulated factors.

Situational awareness. A 2 (control condition) × 2 (collaboration technology) repeated measures ANOVA detected no significant sources of variance in the analysis (all p > .05). The experimentally manipulated factors did not influence participants' ratings of situational awareness.

Team Communication

To determine the effects of the experimental manipulations on team communications, the mean number of verbal, IM, and whiteboard messages sent was calculated for each condition across trials. However, examination of the mean number of IMs sent indicated that participants did not use this tool for collaboration, preventing further analysis of its impact on team performance.

Verbal communication. A 2 (control condition) × 2 (collaboration technology) × 2 (ABM-team) repeated measures ANOVA revealed statistically significant main effects of UCAV-control condition (F [1, 5] = 20.33, p < .05), ABM-team (F [1, 5] = 11.31, p < .05), and a statistically significant UCAV-control × ABM-team interaction (F [1, 5] = 35.10, p < .05). As illustrated in Figure 3, participants sent more verbal communications in the direct UCAV-control condition compared to the supervisory condition, and the sweep-team sent more verbal messages than the UCAV-team across conditions.

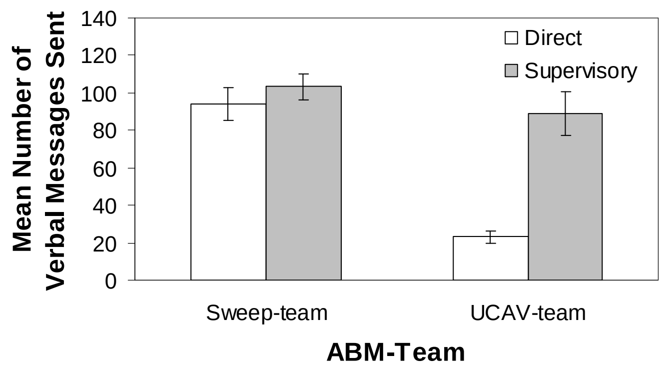

Figure 3. Mean number of verbal messages sent as a function of UCAV-control and ABM-team conditions. Error bars are standard errors.

To further explore the UCAV-control × ABM-team interaction, separate repeated measures ANOVAs were calculated in which UCAV-control condition was analyzed for each ABM-team. For the UCAV-team, a statistically significant main effect of UCAV-control condition was detected (F [1, 5] = 27.94, p < .05), but no such difference was detected for the sweep-team (p > .05). The UCAV-team sent approximately a fourth fewer verbal messages in the direct control condition (M = 23.13, SE = 3.48) compared to the supervisory control condition (M = 88.71, SE = 11.65).

Whiteboard communication. A 2 (control condition) × 2 (ABM-team) repeated measures ANOVA detected a statistically significant UCAV-control × ABM-team interaction, F (1, 5) = 8.11, p < .05.

To further explore the UCAV-control × ABM-team interaction, separate repeated measures ANOVAs were calculated in which UCAV-control condition was analyzed for each ABM-team. For the UCAV-team, a statistically significant main effect of UCAV-control condition was detected (F [1, 5] = 7.98, $p < .05$), but no such difference was detected for the sweep-team ($p > .05$). The UCAV-team sent approximately a third fewer whiteboard images in the direct control condition (M = 5.83, SE = 1.25) compared to the supervisory control condition (M = 17.33, SE = 5.04).

Collaboration preference. Items on the post-experimental debriefing questionnaire asked participants to separately estimate the usefulness of and satisfaction from communicating using the 3 different tools available in the experiment (verbal, IM, DRAW). Participants were asked to rate the three tools on a scale of 0 to 100, where 0 was low usefulness or satisfaction, and 100 was high usefulness or satisfaction. Participants were also asked to justify the ratings they gave each tool. Mean participant ratings for each tool are presented in Table 1.

Table 1. Mean participant ratings of the usefulness and satisfaction of each collaboration tool. Values in parentheses are standard errors.

Tool	Usefulness	Satisfaction
Verbal	98.33 (1.67)	95.83 (4.17)
IM	3.33 (1.67)	2.50 (1.71)
DRAW	76.67 (6.41)	80.00 (7.30)

As indicated in Table 1, participants rated verbal communication to be the most useful and most satisfying tool for collaboration, with the DRAW tool as a close second, and ratings of IM as near zero. For verbal communication, the most common explanations for the above ratings were that verbal was the easiest (4 participants) and fastest (3 participants) collaboration method available. The most typical responses to the DRAW tool were that it was useful for communicating the spatial locations of enemy targets (6 participants) but that it was generally too slow for most communication (2 participants). Overwhelmingly, participants argued that IM was impractically slow for collaboration, given the high temporal pressures of the SEAD mission simulation (6 participants).

Discussion

The current study was an initial, exploratory attempt to characterize team performance, workload, and situational awareness associated with direct and supervisory control of UCAVs by ABMs coupled with several collaboration technologies in a SEAD mission setting.

UCAV Control

Team performance. The effects of UCAV-control condition on team performance were complex, and interestingly, not limited to the ABM-UCAV/operator team. Superficially, these effects appear disparate and inconsistent across indices of team performance. When viewed holistically, however, they may indicate a shift by the ABM-UCAV in the direct UCAV-control condition to an acceptance of riskier decisions in pursuit of task goals.

This viewpoint may be supported by the increase in fighter asset losses and the decrease in launch inefficiency by the sweep-team under direct control conditions. Within the simulation, the responsibilities of the sweep-team were to protect UCAV-team assets from enemy MiGs. If the ABM-UCAV adopted a riskier decision making strategy under direct control conditions, this may have led to the acceptance of more MiG-vulnerable UCAV-team asset deployments. This posture would then necessitate fighter asset engagements under less ideal circumstances as the sweep-team attempted to meet their task objectives, resulting in increased fighter asset losses and more efficient sweep-team launch strategies to replace those killed assets. Further compounding the issue, the shift to a riskier decision-making strategy is not supported by a concomitant increase in the number of enemy targets destroyed for either ABM. Overall, direct control of UCAV assets by the ABM-UCAV resulted in subtle, yet substantial, negative impact on team performance.

Workload and situational awareness. Participants' ratings of workload and situational awareness were unchanged by UCAV-control condition. The lack of significant workload change under direct UCAV control is of note. Three potential explanations may account for this. First, it may be that increased workload associated with direct UCAV control may be equally offset by the reduction of workload related to operator supervision (i.e., both UCAV-control conditions resulted in equal). This explanation, however, does not adequately explain the shifts in team performance observed under direct UCAV control.

Alternatively, it may be possible that participants in the role of ABM-UCAV offset additional workload associated with direct UCAV control by accepting riskier task strategies, as discussed previously. As noted by Singleton (1989), if the workload demands of a task exceed operators' abilities to manage, a skilled operator may adjust their performance strategies to compensate. One such adjustment may be to expend less effort in meeting task demands, leading to a decrement in task performance (Wickens & Hollands, 2000).

Finally, the competition and game-related nature of the SEAD task may have motivated participation in ways that diminished the negative effects of direct UCAV control. It is possible that participants in the direct control condition expended more effort and yet reported no changes in workload and situational awareness because they were sufficiently engaged with the task. Support for this viewpoint comes from previous research linking task engagement to subjective energy and performance on difficult, attentionally demanding tasks (e.g., Matthews & Westerman, 1994). In other words, participants may have been insulated against the negative effects of direct UCAV control on workload and situational awareness through motivation and engagement with the task.

Collaboration Technologies

Team performance. Access to the virtual whiteboard in the current experiment resulted in poorer team performance, as indexed by the number of bomber and UCAV assets killed. This may potentially be attributed to participants' need to switch attention between the DDD and DRAW displays, perhaps frequently, to utilize the information provided by the whiteboard image. The additional time required to shift attention from the DDD display, acquire and process information from the DRAW image, and then shift attention back may have been sufficiently distracting to result in the performance decrements observed.

Participants may also have adopted an inappropriate display-sampling strategy focused on obtaining information from whiteboard images, resulting in insufficient attention to SEAD tasks, and ultimately, poorer team performance. As noted by Wickens and Hollands (2000), individuals have a tendency to seek more information than they can process and integrate quickly. Under conditions of temporal demand, such as those of many C2 environments, this may result in impaired decision making as a consequence of the information-rich setting (Wright, 1974).

Interestingly, participants' ratings of the DRAW tool were seemingly insensitive to this decrement, as it was rated very highly in both usefulness and satisfaction by all participants. This may indicate that personnel in C2 environments need substantial training, beyond functional literacy, with whiteboard software to develop optimal strategies for sampling and interpreting whiteboard images under temporally demanding conditions.

Workload and situational awareness. Access to a virtual whiteboard in this experiment did not affect participants' ratings of workload and situational awareness. It may be that the additional expenditures of time and effort associated with sending, receiving, and interpreting whiteboard images offset any positive impact those images may have had on workload and situational awareness. This viewpoint is particularly interesting in light of participants' comments about the utility of communicating the spatial locations of enemy targets using whiteboard images. Participants may have overestimated the utility of a virtual whiteboard for communicating spatial information, but misperceive the associated costs to team performance.

Overall, the results raise concerns over utilizing a whiteboard for collaboration in time-sensitive situations, at least as it was utilized in this experiment. If extensive training with the tool is necessary to overcome the performance impairments observed, then a more efficient solution may be to limit its use to collaborative environments that are not temporally demanding. Allowing personnel to communicate using this innovative medium under such conditions may facilitate group performance and group satisfaction in distributed teams without the associated performance deficits observed in this experiment.

Conclusions

As an initial, exploratory attempt to characterize team performance associated with several UCAV control schemes and collaboration technologies in a SEAD mission setting, the current experiment was relatively successful. The results of the experiment raise substantive questions about the ability of ABMs to successfully carry out SEAD mission objectives under direct UCAV control, and about the effectiveness of whiteboard communications in C2 environments. Both direct UCAV control and the collaborative technologies investigated in this experiment may exert widespread negative effects on team performance in a complex and unanticipated manner.

Overall, the current experiment offers some insight into the multifaceted human factors concerns that will impact future SEAD mission operations, while simultaneously provoking further questions about such operations. Addressing these issues is necessary to ensure successful future operations in command and control environments.

Acknowledgements

The authors would like to thank Rebecca Brown and Judy Lee (General Dynamics AIS), and Robert Bolia and Brian Donnelly (AFRL), for their efforts related to this project.

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