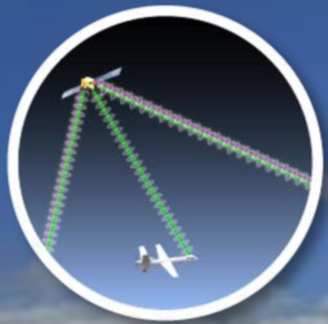

Unmanned Aircraft Systems (UAS) Integration in the National Airspace System (NAS) Project

Multi-UAS HITL – Primary Results

&

Automation Workshop Summaries

Presented to:

SARP Open Day – September 18, 2018

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Background

- NASA’s Phase 1 UAS-NAS research assumed no more than one vehicle per pilot
  - Developed extensive detect and avoid (DAA) display, alerting, and guidance requirements
  - Did not account for multi-UAS control
- Demands for increased scalability of UAS-NAS operations are expected to create need for new DAA system requirements for multi-UAS control
  - New DAA HMI designs for 1:N and M:N configurations
  - Increased automation support concepts
- However, increasing the number of vehicles under operator control has often been associated with degraded performance
  - The exact number of UAs that can be supported is largely a function of the level of automation support and task load (Cummings et al., 2007)

Previous Research on Multi-UAS Operations

- Multi-UAS control results in a considerable increase in workload, with subsequent decrease in situation awareness and efficiency (Fern et al., 2018)
  - Operators max out working memory, fail to process information from multiple sources, and sub-optimally utilize assets (Porat et al., 2016)

- A performance "bottleneck" occurs as a result of toggling between information/assets
  - Toggling between information sources negatively impacts performance (Draper et al., 2008; Fern et al., 2011)
  - This bottleneck still remains *even with better* automation and interfaces (Hancock et al., 2007)

- To mitigate burdens from multi-UAS, researchers have suggested increased levels of autonomy (Cummings et al., 2007)
  - Higher autonomy must be reliable as it can lead to loss of SA and consequently poorer performance (Dixon et al., 2004; Ruff et al., 2002, 2004)
  - Needs consensus between human and automation to improve performance (Cummings et al., 2010)

- **Research agrees that system performance is context dependent – how much automation is available, how well has it been designed, and how difficult is the task?**

Experiment Objective

- Conduct a HITL simulation to investigate issues related to the integration of the DAA system into a multi-UAS HMI design
  - Examine viability of 1:N operations with Phase 1 DAA alerting & guidance
  - Identify needs for automation capabilities
  - Inform potential HMI design modifications for M:N operations

- Representative Phase 1 DAA system and operating environment
  - Medium-to-Large size UAS
  - Class E airspace (simulated Oakland Center, ZOA40/41)
  - Class 1 DAA system – no collision avoidance system included
    - DAA alerting and guidance conforms with Phase 1 Minimum Operational Performance Standards (MOPS)
  - Vigilant Spirit Control Station (AFRL) served as ground control station

- High task load to identify potential bottleneck in DAA system performance

Experimental Design

- Independent Variable (within-subjects)
  - Number of UAs pilot controls simultaneously (1:N)
    - 1:1
    - 1:3
    - 1:5

- Scripted Conflict Variables
  - "Focused" vs. "Unfocused" Intruder
    - Pilot can only focus on one UA at a time in multi-UAS conditions
  - Single vs. Multi-Threat Encounter
    - 1 UA: two intruders in conflict with one ownship simultaneously
    - 3 or 5 UAs: single-intruder conflict with two separate ownships simultaneously
      - NOTE: multi-threat encounters were always a Corrective DAA at First Alert
  - Threat Type at First Alert
    - Corrective DAA or DAA Warning

Experimental Design

- Dependent Variables
  - Measured Response Time
    - Aircraft Response Time
    - Time off Course
  - Separation Performance
    - Rate & Severity of Losses of DAA Well Clear (LoDWC)
    - Maneuver Preference
  - Mission Task Performance
    - Total # of Missions Completed
    - Compliance Rate
    - Time on Target (Efficiency)

Test Setup

- 15 participants
  - 2 pilots/day flying simulated UAs in the same sector simultaneously
  - Average age: 35.63 years
  - Average manned flight hours: 1,292 hours
  - Average unmanned flight hours: 1,701 hours
  - **One pilot's data had to be removed due to poor performance**
    - Met 'extreme negative outlier' criteria for response times and loss of well clear rates

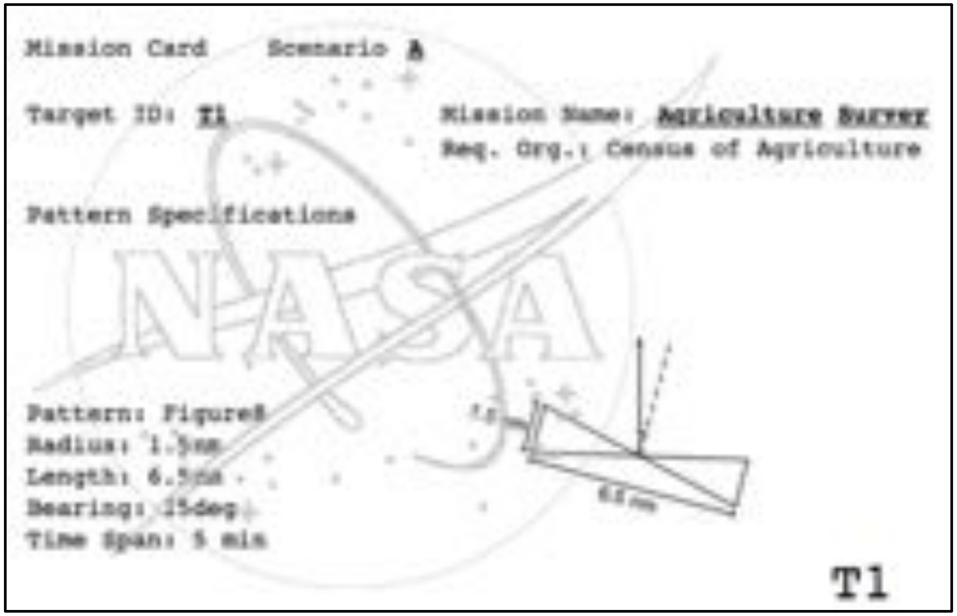
- Three experimental trials (40 minutes each)
  - 1 trial per Number of UA condition
  - Counterbalanced

- Ownship configuration
  - Generic MQ-9 Reaper model
    - Cruise speed: 110-140 kts
    - Mission altitudes: 6-12,000 MSL
    - Climb/descent rate: 1000 ft/min
    - Surveillance: ADS-B In, RADAR

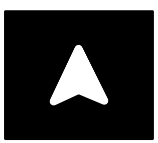
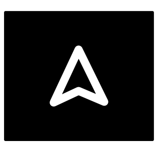
Scenario Design

- Pilot Tasks
  - DAA Task
    - 4 single-threat encounters per trial
    - 1 multi-threat encounter per trial
  - Standard Mission Task
    - Loiter over specified areas of interest with prescribed shape, size and duration
    - 18 available per trial
  - Sensor Monitoring Task
    - High-priority
    - Increased task load
    - 2 assigned per trial

- *Pilots were asked to coordinate with ATC when changing area of interest or maneuvering for traffic*



Phase 1 DAA Alerting Logic

Icon	Alert Level	Expected Pilot Response	DAA Well Clear Criteria	Time to Loss of Well Clear	Aural Alert Verbiage
	DAA Warning Alert	Maneuver immediately	HMD = 0.66 nm DMOD = 0.66nm ZTHR = 450 ft modTau = 35 sec	25 sec	"Traffic, Maneuver Now" x2
	Corrective DAA Alert	Maneuver following ATC approval	HMD = 0.66 nm ZTHR = 450 ft modTau = 35 sec	55 sec	"Traffic, Avoid"
	Preventive DAA Alert	Monitor traffic; maneuver not currently required	HMD = 0.66 nm ZTHR = 450-700 ft modTau = 35 sec	N/A	"Traffic, Monitor"
	Guidance Traffic Alert	No maneuver required	Associated with banding outside current course	N/A	N/A
	Remaining Traffic	No maneuver required	Within surveillance field of regard	N/A	N/A

Video Clip with **5 UAs**

Hypotheses

- Research Question
  - How does multi-UAS control configuration impact pilots' ability to maintain DAA well clear and perform mission tasks?

- Hypotheses:
  - As number of UAs under control increases, performance will degrade:
    - Slower response times
    - More time spent off course
    - Higher rate & severity of LoDWC
    - More time on task per mission (i.e., less efficient)
  - *Except for*:
    - Number of missions completed expected to increase with more UAs

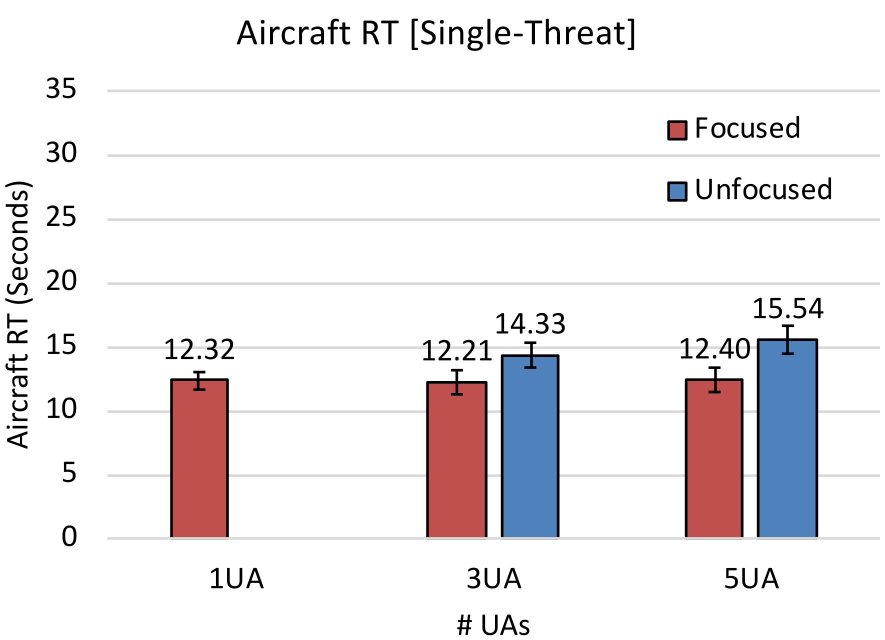
MEASURED RESPONSE

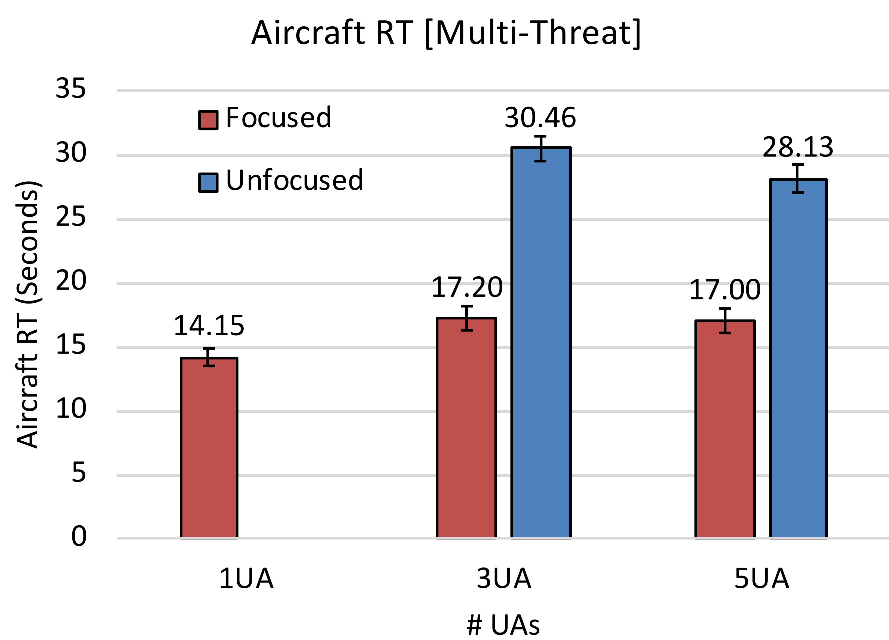
Metrics:

- Aircraft Response Time (AC RT): time elapsed from the onset of the relevant DAA alert and the first upload sent to the vehicle in response
- Time Off Course: amount of time pilots spent off route due to a maneuver for traffic

Aircraft RT

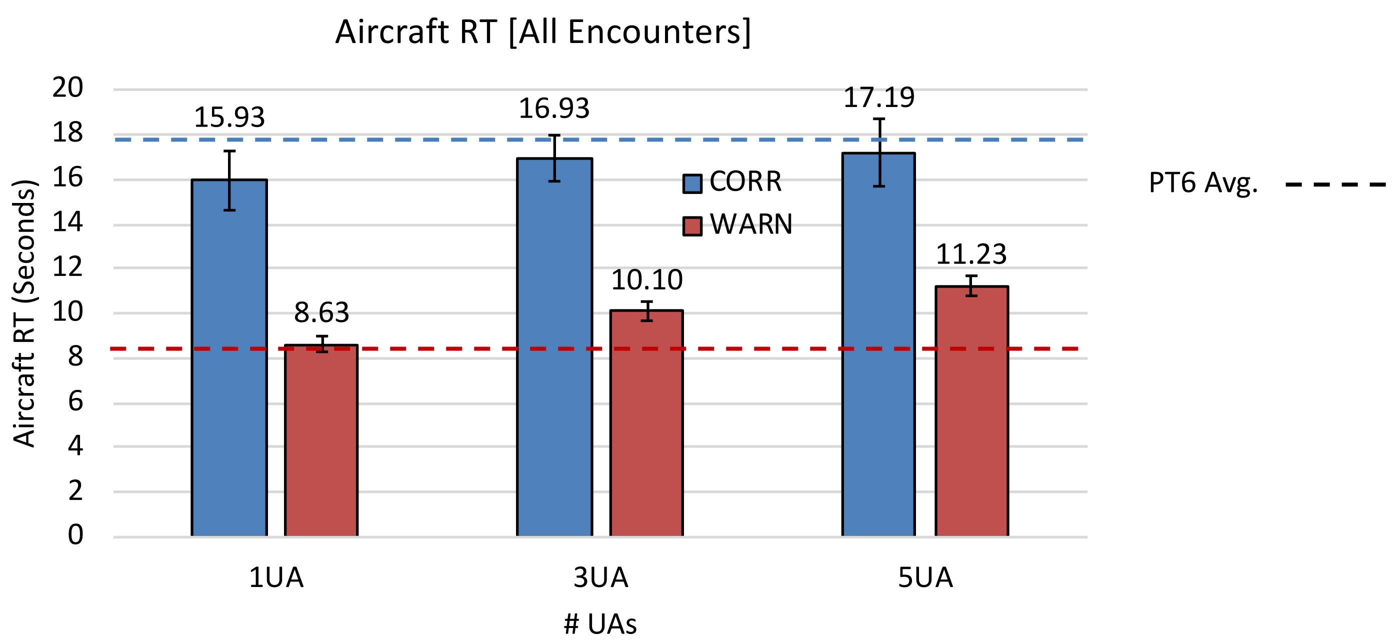
- Conflict type had larger impact on Aircraft RT than number of UAs alone
  - Single-Threat, Focused intruders have identical RT
  - Multi-Threat, Unfocused intruders had largest RT





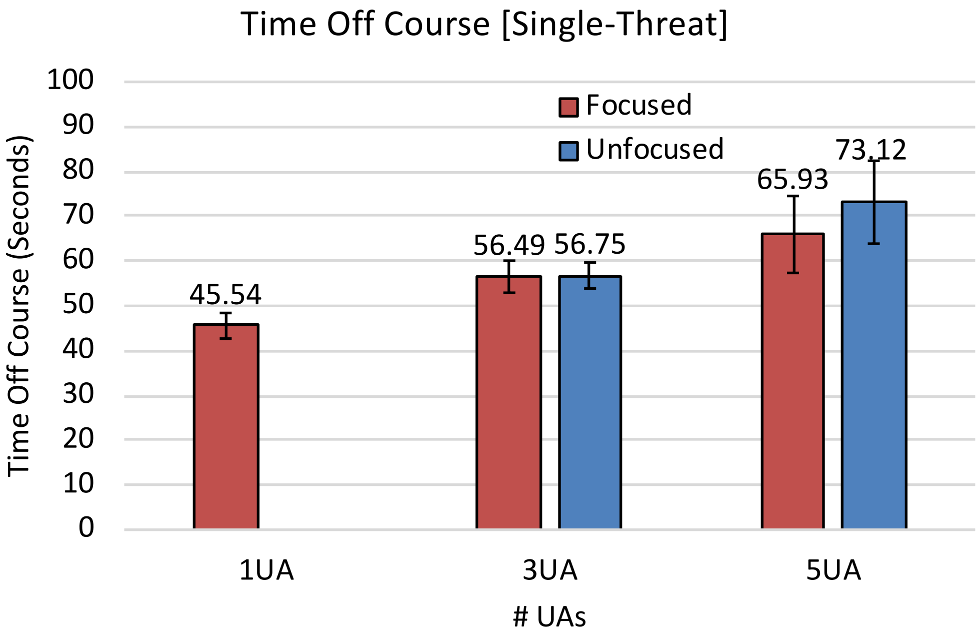
Aircraft RT

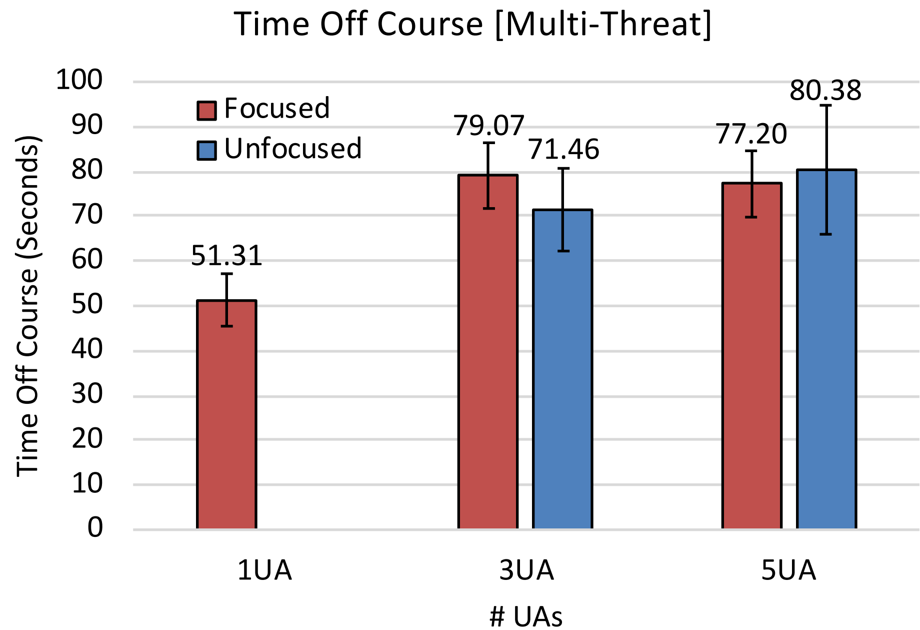
- Pilots respond faster to Warning alerts compared to Corrective alerts in both the single and multi-UAS configurations
  - Did not see an effect of Focused vs Unfocused intruders
- Consistent with past research – although Warning response times begin to creep up with additional UAs



Time off Course

- Time off course increases with number of UAs under control
  - No clear effect of Focused vs. Unfocused
  - Impact of number of UAs stronger in Multi-Threat encounter cases





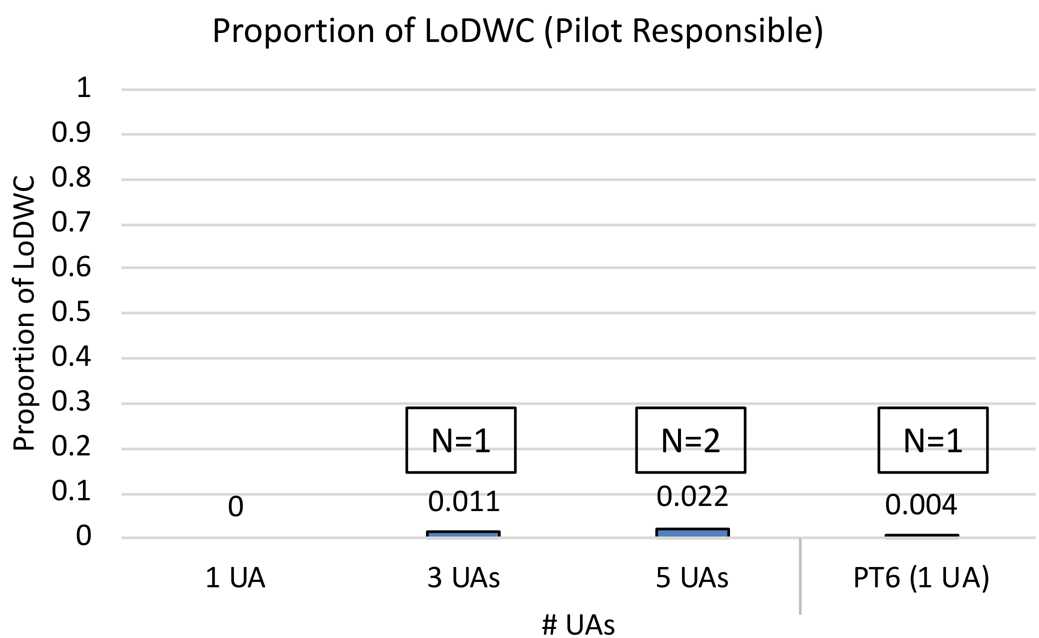
SEPARATION PERFORMANCE

Metrics:

- Loss of DAA Well Clear (LoDWC) Rate: the rate of losses of DAA well clear out of all conflicts predicted to lose DAA well clear (i.e., generated a Corrective or Warning DAA alert)
- Severity of LoDWC (SLoWC): percentage of the DAA well clear volume penetrated by the intruder (higher % = greater penetration)
- Avoidance Strategy: the type of maneuver made by the pilot in response to a conflict

LoDWC Results

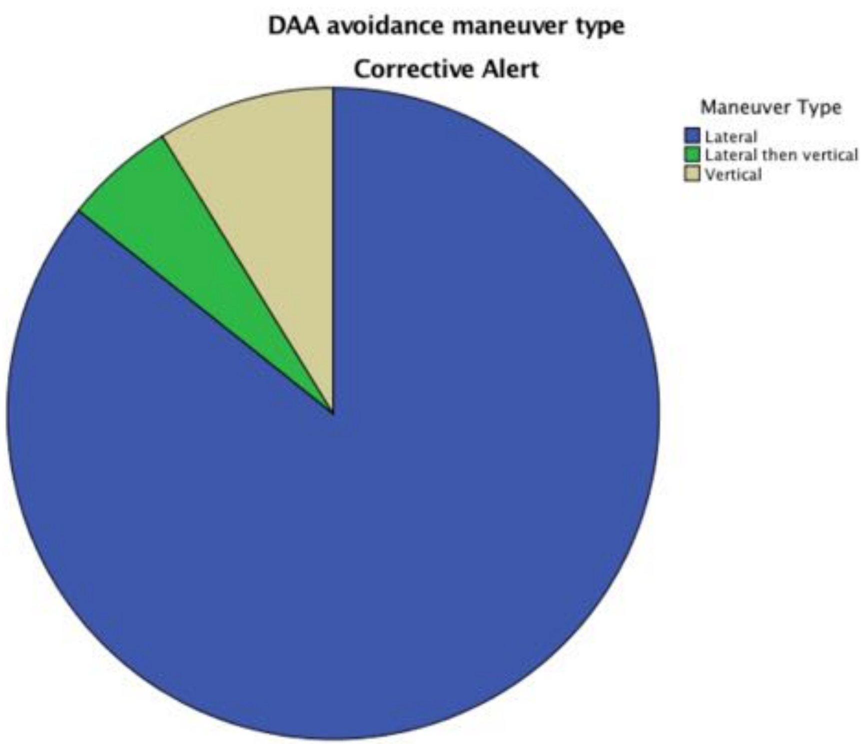
- 3 pilot-responsible LoDWC **total**
  - 2 were a result of returning to course too soon following an avoidance maneuver
  - 1 was a result of the pilot taking too long to respond to the alert (occurred in the 5 UA condition)
  - Note: there were 2 LoDWC with the pilot *not* at fault – caused by inconsistent bug with vehicle performance



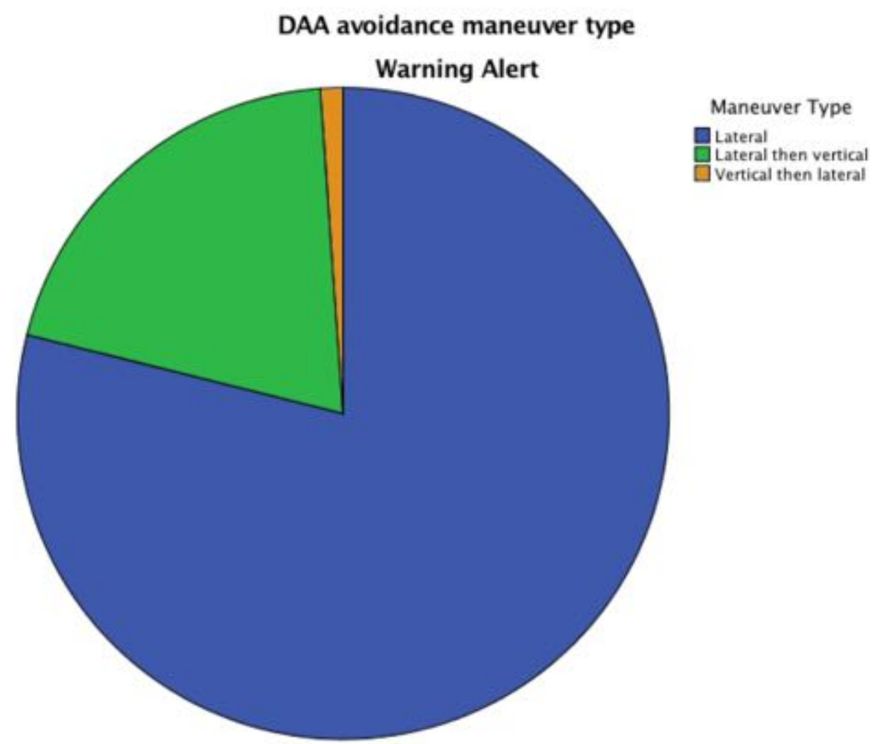
- Severity of LoDWC (SLoWC) < 10% for all pilot-responsible LoDWC

Avoidance Strategy

- Majority of conflicts avoided with lateral maneuvers
- Increase use of blended (i.e., lateral and vertical) maneuvers in response to Warning-level alerts



Maneuver	Frequency	Percent
Lateral	78	85.7%
Lateral then vertical	5	5.5%
Vertical	8	8.8%



Maneuver	Frequency	Percent
Lateral	71	78.9%
Lateral then vertical	18	20.0%
Vertical then lateral	1	1.1%

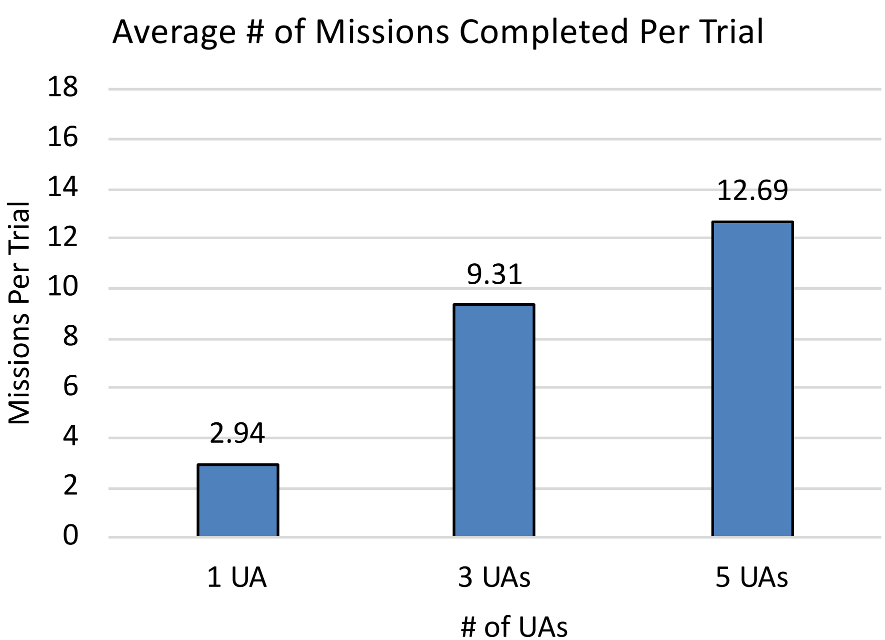
MISSION TASK PERFORMANCE

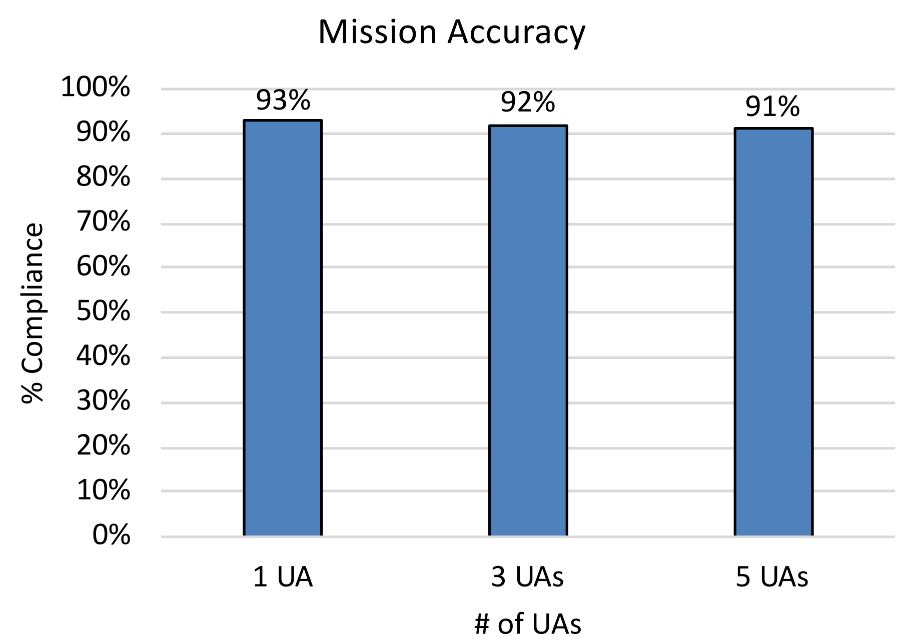
Metrics:

- # Missions Completed : average number of missions completed per trial (max = 18)
- Mission Accuracy: number of mission tasks completed correctly
  - I.e., correct loiter diameter/shape/orientation
- Average Time Over Assigned: the amount of time a given UA spent in the loiter pattern *beyond* what was assigned
  - Example: if pilots spent 5min 30sec in loiter when 5min was the assigned loiter duration, time over assigned = 30sec

Mission Task Performance

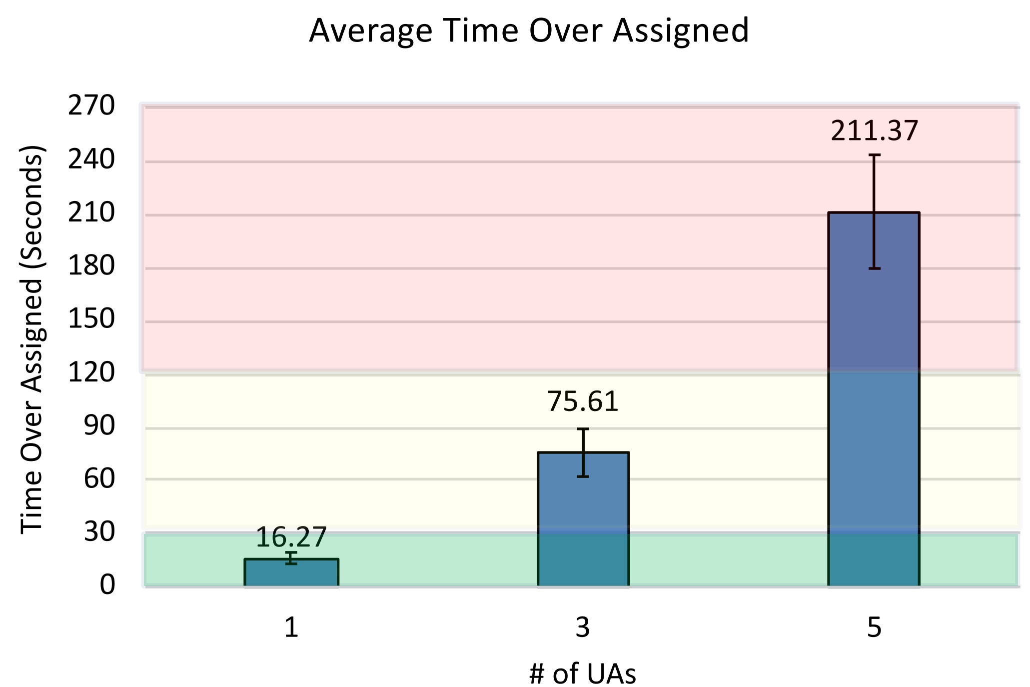
- Higher number of missions completed with more UAs under control
  - Small number completed in 1 UA condition largely a result of time it took to transit from target to target
- Nearly identical compliance rate across all conditions
  - Incorrect pattern type & early pattern exits were most common errors





Mission Task Efficiency

- Mission task efficiency dropped with increasing number of UAs
  - 5 UAs led to inefficient use of assets in particular
  - 1 UA led to extremely efficient use of vehicle



Grade	Performance criteria	1 UA	3 UAs	5 UAs
A	Within 30sec of assigned time	87%	33%	25%
B	30-120sec over assigned time	9%	47%	24%
C	120+ sec over assigned time	-	15%	45%
Incomplete	Too little time	4%	4%	4%

IMPLICATIONS / PATH FORWARD

Results Summary

- Research Question
  - How does multi-UAS control configuration impact pilots' ability to maintain DAA well clear and perform mission tasks?

- Hypotheses:
  - As number of UAs under control increases, performance will degrade:
    - Slower response times
      - Response times were more seriously impacted by conflict type than by number of UAs under control
      - Unfocused and multi-threat encounters resulted in much longer response times
    - More time spent off course
      - Increased with more UAs under control; less impacted by conflict type
    - 🚫 Higher rate & severity of LoDWC
      - Number of LoDWC extremely low (with low severity) across all conditions
    - More time on task per mission (i.e., less efficient)
      - Efficiency extremely high for 1 UA but plummeted for 5 UA
  - *Except for*:
    - Number of missions completed expected to increase with more UAs
      - 5 UA allowed pilots to ~66% of total missions, 1 UA only ~15%

Conclusions

- DAA system proved surprisingly adaptive to multi-UAS control for preventing LoDWC
  - All number of UA conditions were comparable to Phase 1 (1:1 control) results
  - Did **not** implement any multi-UAS automation support
- Number of UA had much stronger impact on mission task performance
  - Pilots were able to complete more mission tasks at cost of reduced efficiency
- Suggests – in this context – that automation support tools for completing and managing mission tasks would be most appropriate
  - Especially for ensuring efficient use of assets

Next Steps

- Investigate pilot performance with DAA system at increased scalability
  - 10+ UA - how does system need to adapt (if at all) at these numbers?
  - Examine M:N operations – what technologies are required to support ’sharing’ of vehicles between ground stations
  - Apply to Urban Air Mobility (UAM) context

- Apply Human Autonomy Teaming technologies to multi-UAS pilot directed interface
  - Transparency
  - Bi-directional communications

- Develop ‘working agreements’ and/or ‘plays’ to aid operators in multi-UAS control
  - Working agreement (pre-defined delegation)
    - Example: if I have alerts from one A/C and another gets a WC alert – then the automation has authority to perform automated well clear
  - Plays (real-time delegation)
    - Example: On-board fire detected. Pilot calls “fire” play and the automation then has the authority to release fire suppressant, do fire checklists, etc., while the operator is freed up to contact ATC and troubleshoot

SUMMARIES OF 2 WORKSHOPS ON: HUMAN-AUTOMATION INTERACTION CONSIDERATIONS FOR UAS INTEGRATION

1st Workshop (Washington, DC; Jan 2018)

- Purpose: 2-day workshop aimed at advancing the understanding of the human factors/human systems integration issues associated with the full integration of Unmanned Aerial Systems (UAS) into the National Airspace System (NAS)
  - Highlight existing human factors and human-systems integration research & identify opportunities to address gaps and opportunities in research

- Themes:
  1. Controllers Must Be Involved in the Solutions – concern was raised repeatedly that the focus on pilot/operators can leave out issues involving ATC
  2. The System Is Changing, Which Requires Planning - important to consider from multiple perspectives, including certification, regulation, policy guidance, and the development of mental models that are shared by all actors in the system
  3. Training and Procedures Will Become Increasingly Important - designs that are focused on assisting humans to be successful will reduce the need for repetitive training and will contribute to system-wide performance
  4. Bad Guys, Surprises, and Unexpected Behaviors - illicit use of UASs in controlled airspace needs to be considered

2nd Workshop (Columbus, OH; May 2018)

- Purpose: apply human factors expertise to two uses cases that highlighted increased automation in the domain of UAS integration into the NAS
  - **Use Case 1**: Auto-Collision Avoidance (CA) & Return-to-Course (RTC)
  - **Use Case 2**: Multiple UAS Control
  - Breakout groups focused on documenting potential human-automation architectures and identifying research gaps, such as:

- Auto-CA & RTC:
  - Should the remote pilot be "locked out" of automatic collision avoidance maneuvers, and if so, how should it be done and annunciated to the remote pilot?
  - How should return to course maneuvers be made based on engaged autopilot/autoflight modes (e.g. heading mode, flight plan mode, flight level change, altitude hold)?
- Multiple UAS:
  - What new phraseology should be used for voice communications between remote pilots and ATC for multiple UAS operations?
  - How should alerting be done for multiple UAS?
    - Does the existing warning/caution/advisory structure with master caution/warning indications work? How should individual vehicle issues vs fleet-wide issues be alerted?
  - How should displayed information and alerts be prioritized for the remote pilot in multiple UAS operations? Can automation add/remove displayed information?
  - How should crew rest and breaks for multiple UAS operations teams be structured (look at ATC and airline dispatch practices)?

2nd Workshop (Columbus, OH)

- Automation:
  - How to communicate to the remote pilot automation confidence levels?
  - How to train multiple UAS operations teams on crew resource management (CRM) with automation, especially on when to trust automation and how to anticipate workload bottlenecks?

- General Considerations:
  - Geo-fences may be designed to be “soft,” in that they allow UAS to cross them after confirmation by the remote pilot (i.e., an “ask-first” geo-fence).
    - This may allow UAS with dynamic flight planning capabilities to remain outside controlled airspace unless the remote pilot coordinates with ATC. Crossing a “soft” geo-fence may apply to a subset of vehicles in a multiple UAS operation.
  - The design of automation implementations, whether automatic collision avoidance or multiple UAS control systems, must consider degraded states for the equipment and automation.
  - Troubleshooting and diagnostics information must be considered during the design, including what information to present to the remote pilot for those tasks.

Questions?

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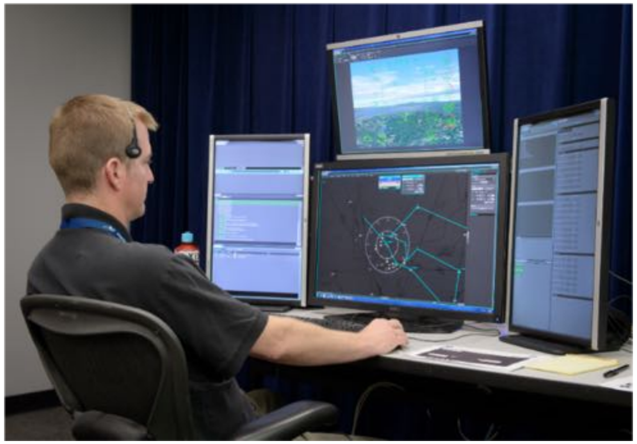
BACKUP

Facilities & Resources

- Collaborative effort:
  - Detect and Avoid
    - Human Systems Integration
    - Modeling & Sim
  - Integrated Test & Evaluation
- Facilities
  - HAT Lab
    - N-262 Rm. 243
  - CVSRF
    - N-257
- DAA System
  - JADEM/DAIDALUS
- LVC Gateway
- Ground Control Station
  - Vigilant Spirit Control Station
    - Traffic display and control interface for pilot tasks -->
    - Isolated in pilot booths
  - Vigilant Spirit Simulation
    - Event generation tool for researcher tasks
    - Located in sim manager area
  - Virtual Reality Scene Generator (VRSG)
    - Image generator for sensor tasks (heads-up display)
- Voice Communication
  - PLEXSYS
    - Push-to-talk headset



Development

- ✓ Integration of multiple ownships for a single GCS with individual DAA systems – impacts JADEM and LVC
- ✓ Additional testing requirements to ensure stability of new, scaled DAA architecture
- ✓ Develop more relevant mission tasks
- ✓ Integration of DAA HMI with VSCS multi-vehicle HMI:

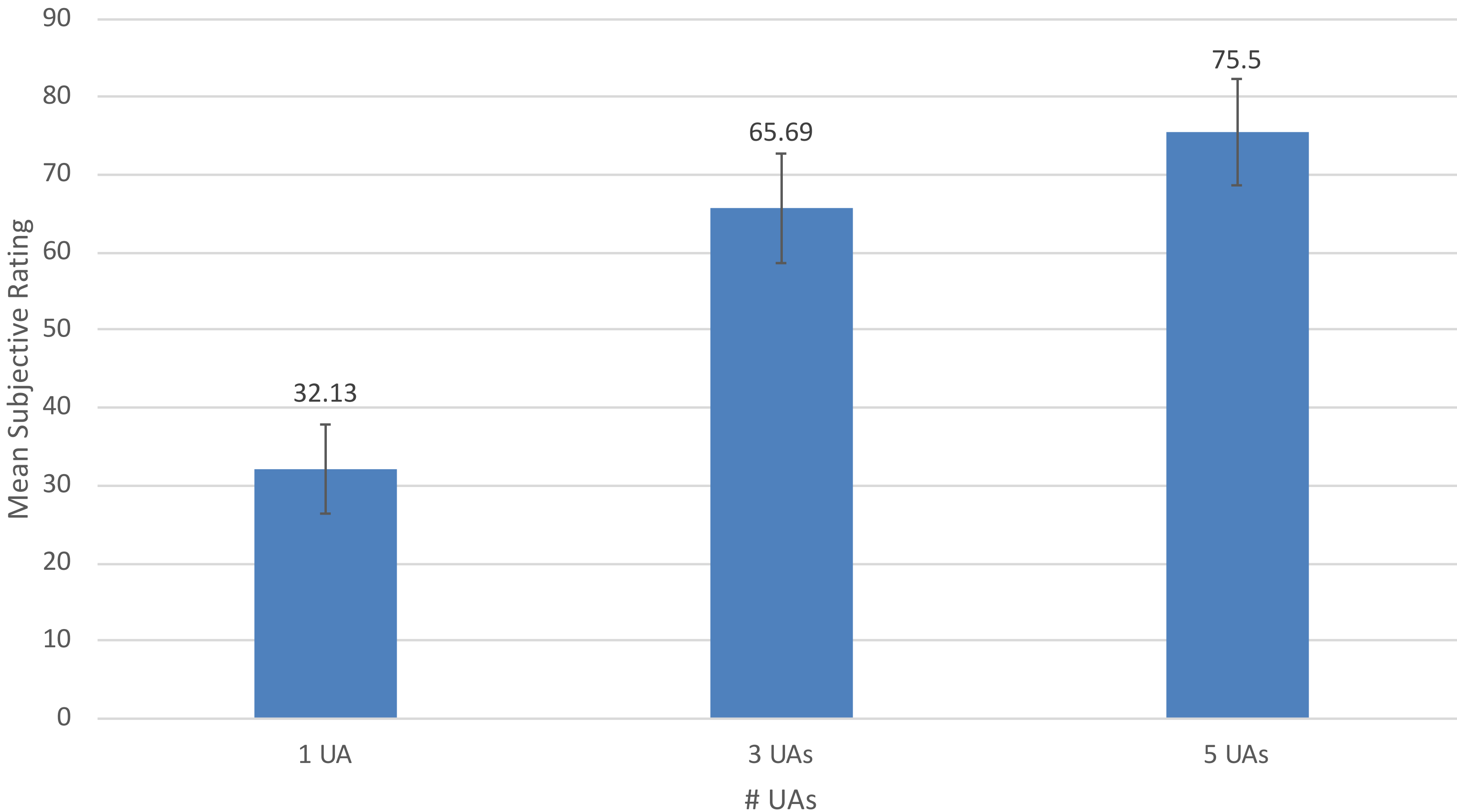
Time on Task Stopwatch

Indicates active DAA alert for unfocused UA, click banner to focus on UA in conflict

SUBJECTIVE RATINGS
WORKLOAD & PERFORMANCE

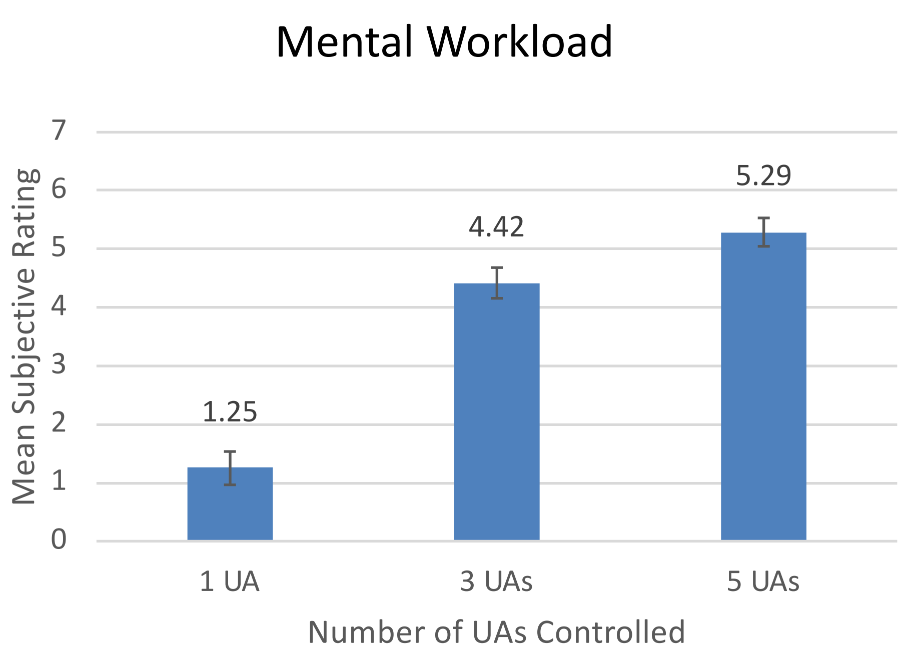
Subjective Results – TLX: Sum

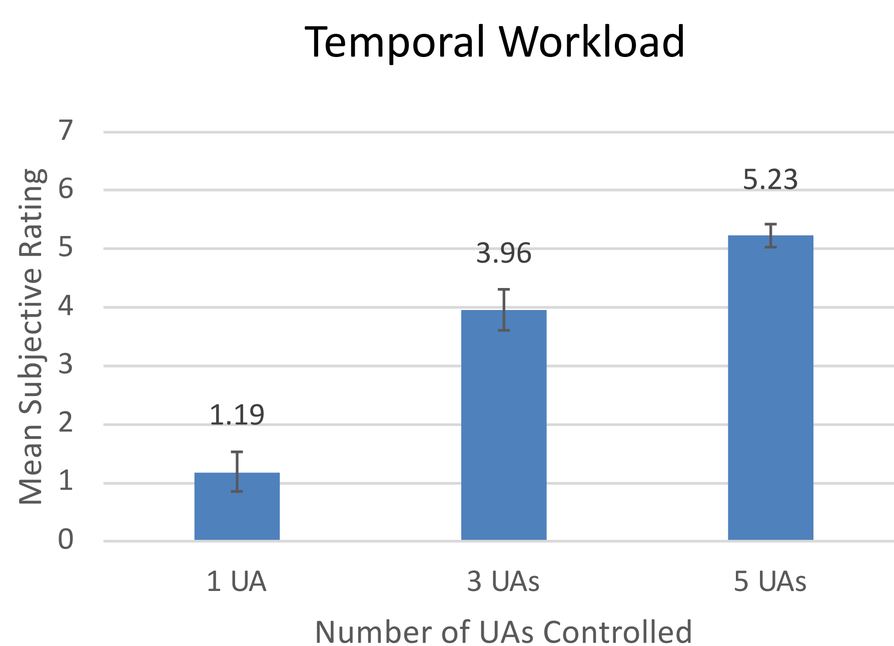
- Overall, pilots experienced higher workload w/ more than 1 UA under their control
  - Regardless of whether they controlled three or five aircraft



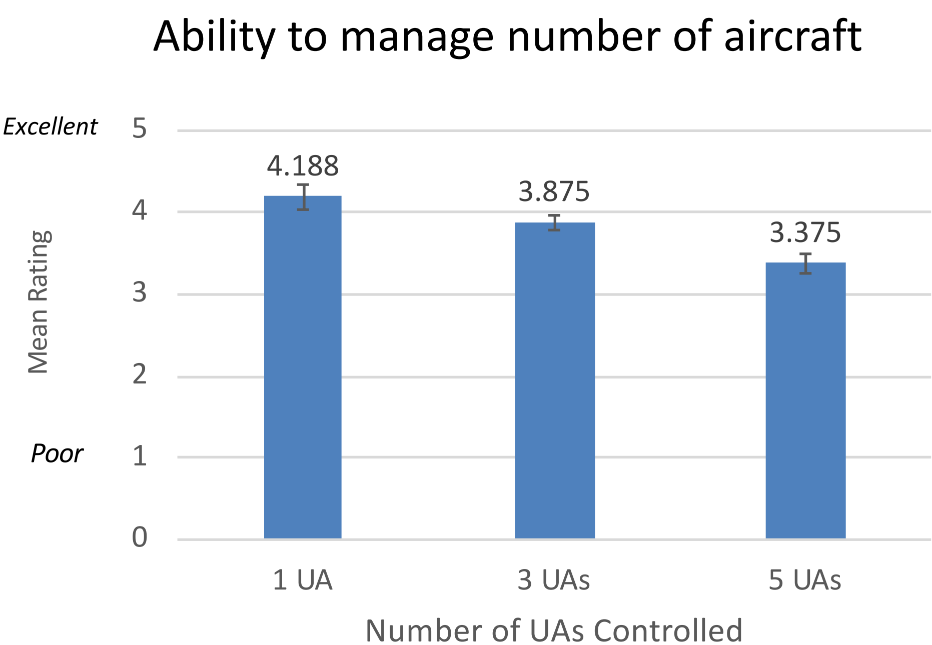
Subjective Results: TLX

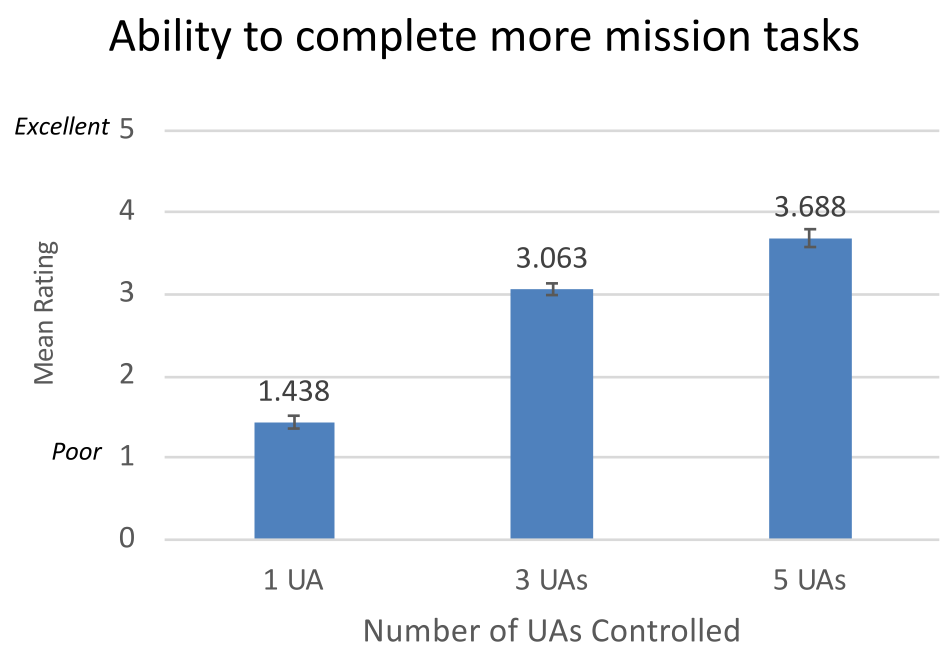
- Participants indicated workload greatly increased as a function of the number of aircraft under their control
  - The 5 UA condition was consistently cited as workload-intensive
    - “Five is definitely the workload max. I would recommend at least two-hour duty cycles because it is exhausting”





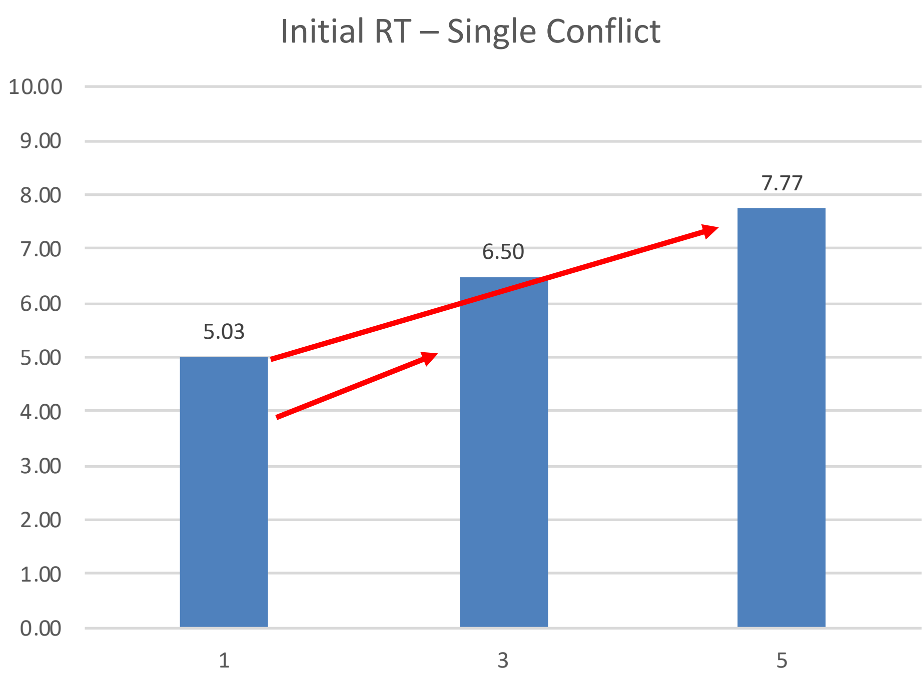
Subjective Results - Questionnaire



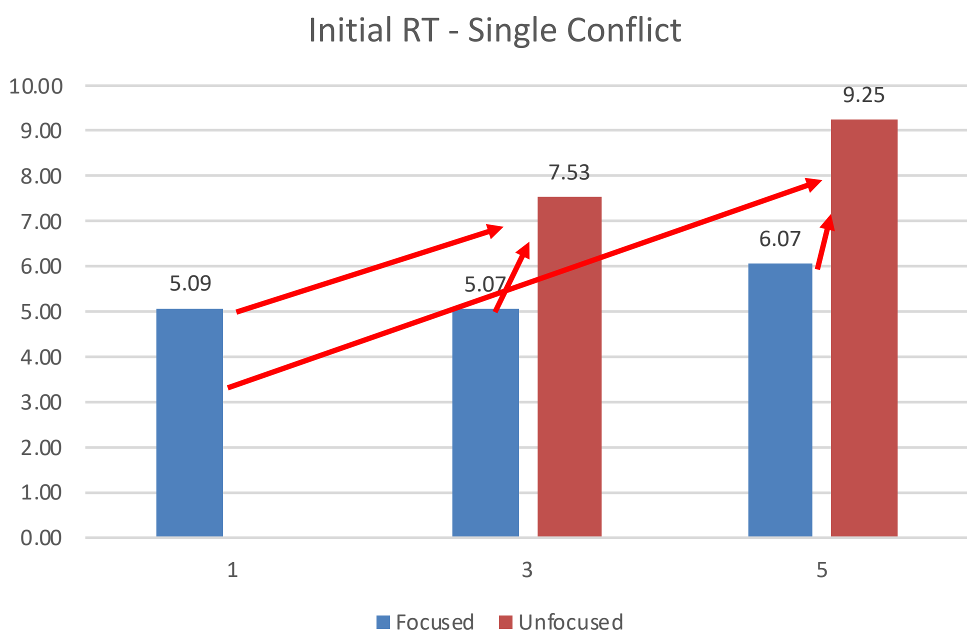


Initial RT w/ Single Threat

- Fastest Initial RTs with 1 UA compared to multiple UAs

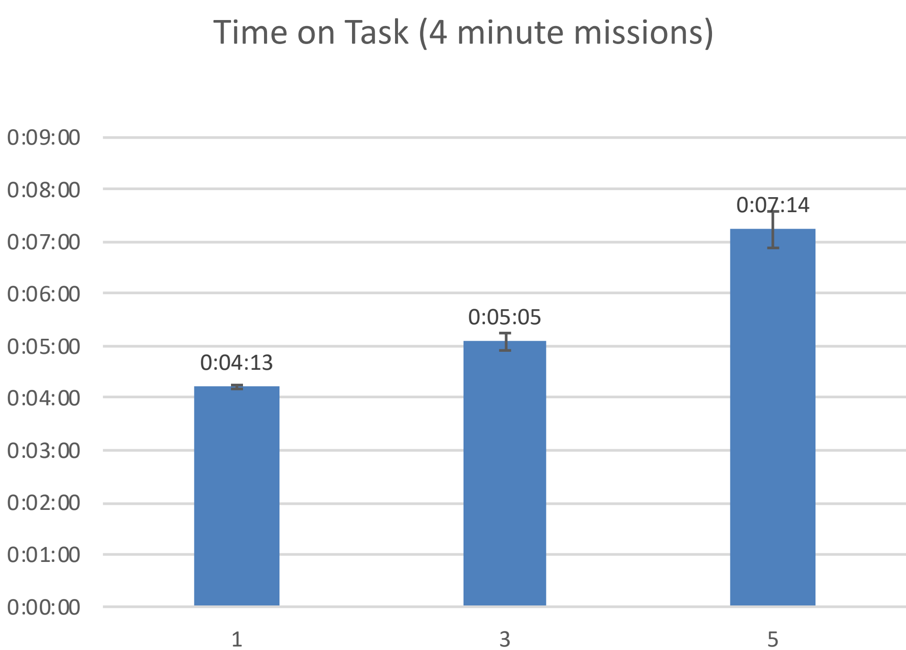


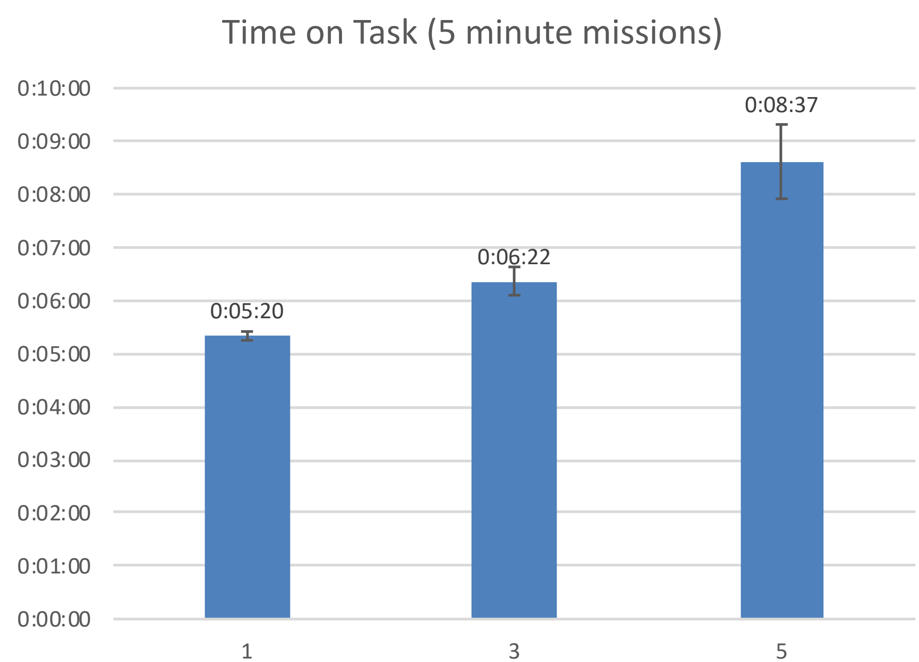
- Due to slower RTs for Unfocused threats:



Mission Task Efficiency

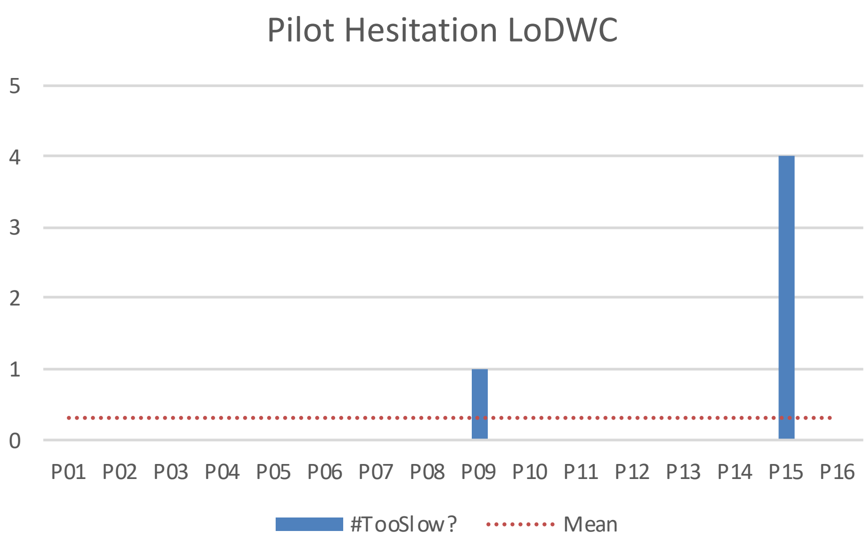
- Longer time on task with more UAs under control
  - Efficiency tradeoff most prevalent with 5 UAs
  - Higher efficiency with shorter missions across all conditions



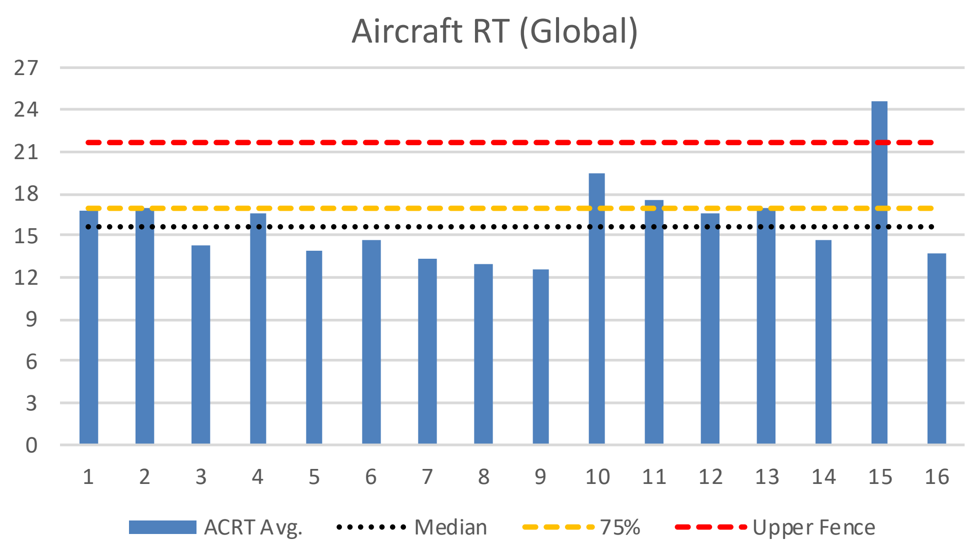


Outlier – P15

Separation



Measured Response Time



Post Sim Questionnaire

- Which factors were most influential when deciding how to maneuver against DAA threats?
  - 56% of pilots agreed that the DAA color bands were helpful
  - 25% found that the bands were able to show the shortest safe heading
  - 19% found the baseball cards were helpful to show threats;
  - 13% found the vector ownship was helpful
  - Other factors only one pilot found was the correct indications of intruding aircraft, knowing aircraft altitude and speed, and knowing airspace restrictions.

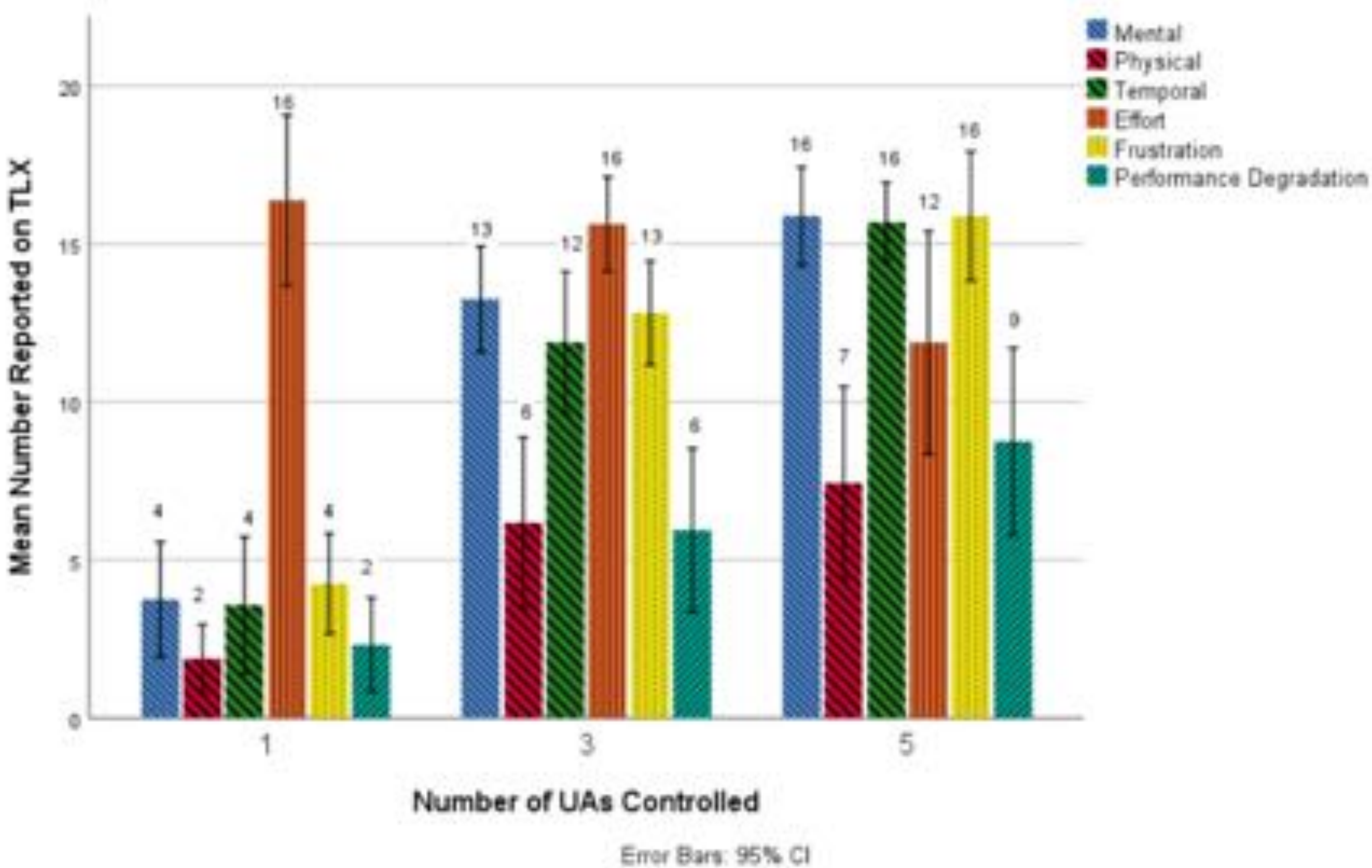
- What were the **disadvantages** of this display when controlling multiple aircraft?
  - 38% disliked the delay in movement or slowness to resolve a threat
  - 32% disliked the layer overlap such as the aircraft turning into traffic
  - 25% found that selecting a finding the heading control bug was difficult
  - 25% disliked not being able to see all the traffic on the map
  - 19% disliked not being able to reorder of baseball cards
  - 19% would prefer the TFR to be red
  - 19% would want the checklists to automatically cross off when a mission was complete
  - 19% did not like the mutually exclusive windows (LTR vs HOLDS)
  - 19% found the DAA symbology was congested sometimes (corrective over redundant or preventative DAA nuisance)
  - 13% would want an all aircraft picture or an altitude stack
  - 13% disliked not being able to press enter.
  - Other factors only one pilot disliked where that the sensor function had longer latency, heads-up display was only on the focused aircraft, and unsure the highest threat when given multiple threats.

Chat RTs

- Increased UAs delayed responses to chat messages
  - Queries on current status of the aircraft
  - Based on data collected from 10 of 16 pilots:

1 UA Chat RT	3 UAs Chat RT	5 UAs Chat RT
0:00:44	00:01:09	0:01:21

TLX Data



Mean Number Reported on TLX
Number of UAs Controlled
1
3
5
0
5
10
15
20
Mental
Physical
Temporal
Effort
Frustration
Performance Degradation
4
2
4
16
4
2
13
6
12
16
13
6
16
7
16
12
16
9
Error Bars: 95% CI