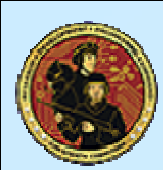


An Investigation of Real World Control of Robotic Assets under Communication Latency

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Long Term Goals

- Communications always a problem once you put the robot into the field
- Scaled guidelines for managing communication limitations with respect to communication latency
- Specifications for interface/system design



Communication Latency Experiments (1 & 2)

- Investigate the effects of communication latency on control performance of UVs and on operator SA
- Focus on the impact of latency for fine control in confined spaces
 - Navigate the robot through courses that simulate a building reconnaissance exercise
- Provide a means to generalize the results to other UVs and tasks





Questions

- How does increased latency duration effect control performance and operator SA?
- How does raising the LOA impact the effects of communication latency?
- What are the effects of varying latency duration in comparison to a constant duration?
- Does the direction in which the latency occurs play a role?



Experiment Variables

- Latency Duration (between factor)
 - None, Short, Medium, Long
 - 0, 1, 2, and 4 sec.
 - Truncated to Short and Long
- Latency Variability (between factor)
 - Constant (hardware delays, satellite)
 - Varying (typical internet – pauses, jumps, dropouts)
- Latency Direction (between factor)
 - Robot to User (R2U)
 - User to Robot (U2R)
- LOA (within factor)

U2R



R2U

Actual Position

Sensor Data



Level of Automation	Roles				
	Endsley and Kaber LOA	Monitoring	Generating	Selecting	Implementing
Teleoperation	Manual Control	Human	Human	Human	Human
Guarded Teleoperation	Action Support	Human and Computer	Human	Human	Human and Computer
Obstacle Avoidance Waypoint Navigation	Decision Support	Human and Computer	Human and Computer	Human	Computer
Autonomous Waypoint Navigation	Automated Decision Making	Human and Computer	Human and Computer	Computer	Computer

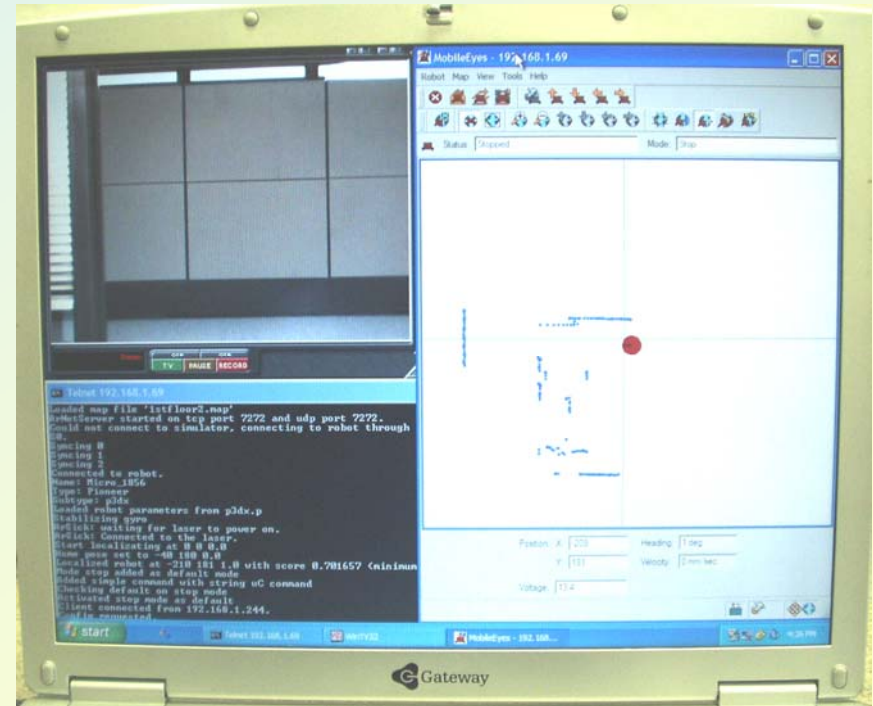
Adapted from M. R. Endsley and D. B. Kaber, "Level of Automation Effects on Performance, Situation Awareness and Workload in a Dynamic Control Task"





Equipment

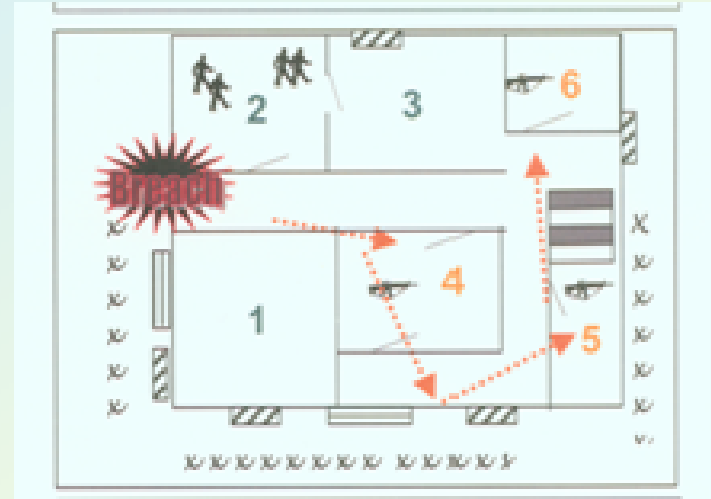
- Equipment
 - Pioneer 3-DX from Activ Media Robotics
 - Pan/tilt zoom color video camera
 - SICK laser range finder
 - Control interface
 - Laser data
 - Video view
 - Joystick & mouse control
- Facility – After hours office space; 4 courses on different floors
- Participants – 16 novices per experiment (32 total)



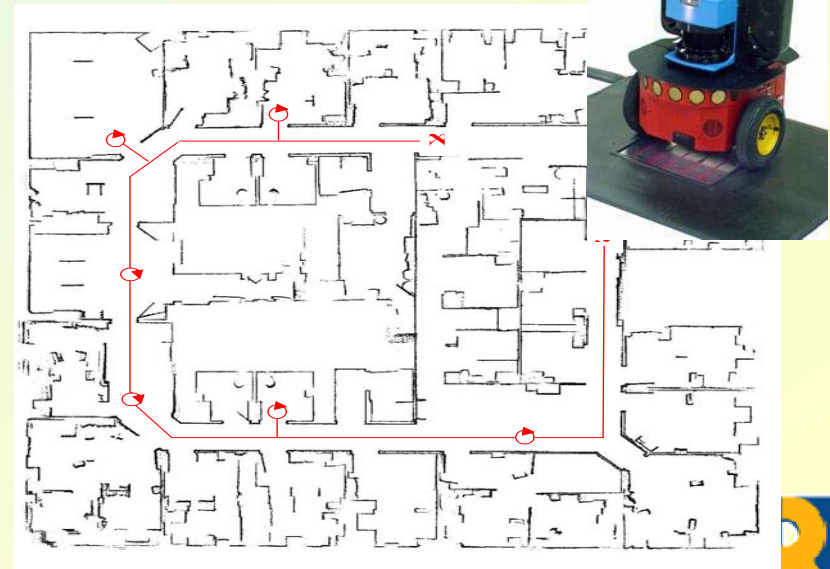


Procedure

- Practice (level of efficiency criterion - time)
- Participants drove a robot through 4 courses that simulated MOUT building reconnaissance under each LOA
- Provided with a map depicting the route, directed recon “spins” in certain rooms/locations
- Timed trials for a sense of urgency
- Asked to try to avoid obstacles and running into walls



Klein Associates, "Military Operations in Urban Terrain (MOUT) Decision Making in Action".





Metrics

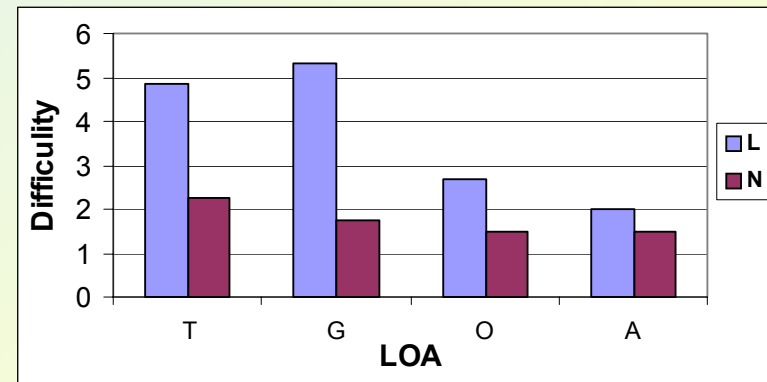
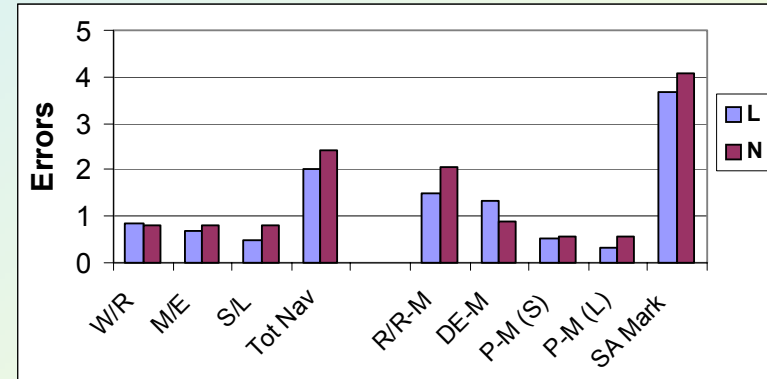
- Performance
 - Time to complete course
 - Number of driving errors
- SA
 - Navigational errors
 - Missing or performing an end point / reconnaissance point in the wrong location (M/E)
 - Entering the wrong room or moving in the wrong direction (W/R)
 - Stopping due to becoming lost (S/L)
 - SA report mistakes
 - Marking the wrong room entered or direction moved (R/R-M)
 - Not marking or marking the wrong location of a driving error (DE-M)
 - Marking the incorrect position of the bot (P-M)
 - Small mistakes
 - Large mistakes
- Subjective questionnaires
 - Post mission subjective difficulty ratings (11 point likert scale)
 - In controlling the robot
 - In maintaining SA
 - Post experiment questionnaire
 - Ranked LOAs from best to worst in terms of ease of control and ease in maintaining SA
 - Estimated percent concentration in each LOA
 - Ratio of control vs. SA
 - Experiment 2 – rerank difficulty





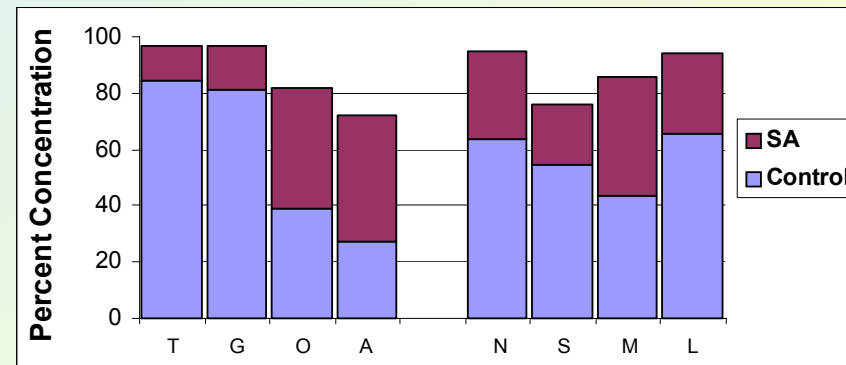
Control Condition

- In general Navigation and SA marking mistakes did not increase between the latency and the no latency conditions, and in many cases actually decreased.
 - This is most likely due to subjects slowing down due to increased control difficulty or switching to a move-and-wait control strategy, both of which allow more time for SA
- However large increase in perceived SA difficulty for lag over no lag in lower LOAs (diminishes as LOA increases)



Control Condition (cont)

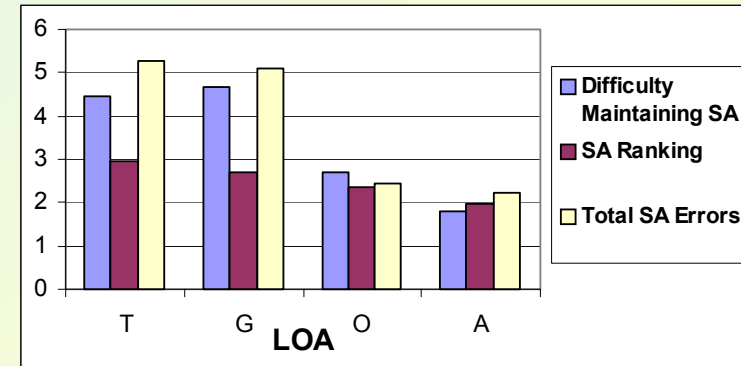
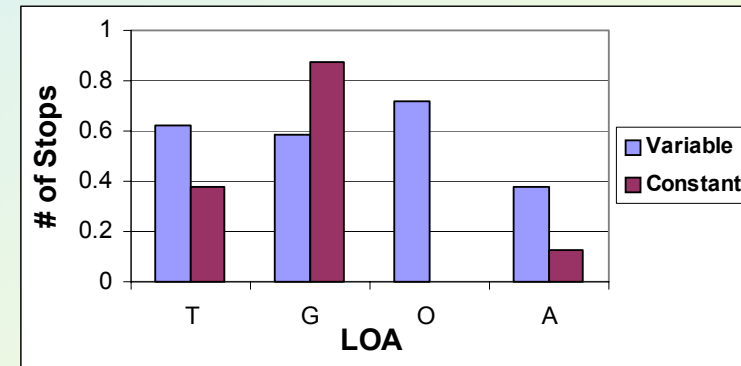
- Lastly another somewhat counter intuitive trend was seen in that a larger percentage of time was estimated for control in the no delay condition than in the other LD conditions.
 - Participants most likely thought SA to be easy when there was no delay, which of course is not the case. Hence they did not give adequate attention to SA, which may be another cause for the increase in navigation and SA report errors.
- Overall conclusion:
 - The existence of latency made SA more difficult to maintain, however this was most likely offset by slowing down when latency existed.
 - Subjects tend to concentrate on control and do not naturally give enough attention to maintaining SA.
 - Increasing the LOA was perceived as helpful for maintaining SA by participants





LOA Results

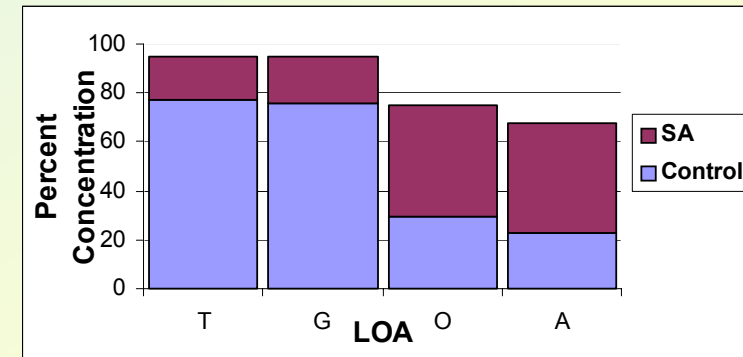
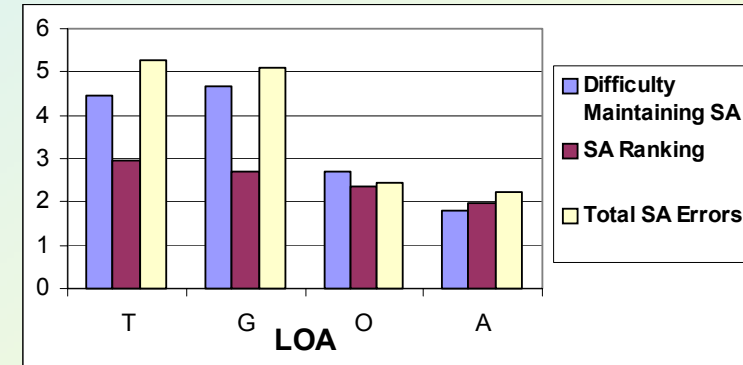
- LOA had little effect on the number of total navigation, W/R, or M/E errors in either experiment
 - Indicates that increasing the LOA is either not necessary to or does not aid subjects in discerning the correct path
- Under constant latency, participants' stopped more due to being lost in lower LOAs, but this effect did not hold under varying latency.
 - This is most likely due to users becoming lost easier when control is more constant
 - Participants probably have not switched to a move-and-wait strategy and hence are not frequently task switching between control to SA and most likely not devoting enough time to SA.
- In general less SA marking mistakes were made in higher LOAs, O and A, than lower ones, T and G.
 - Remembered the actual route taken by the bot better at higher LOAs





LOA Results (cont)

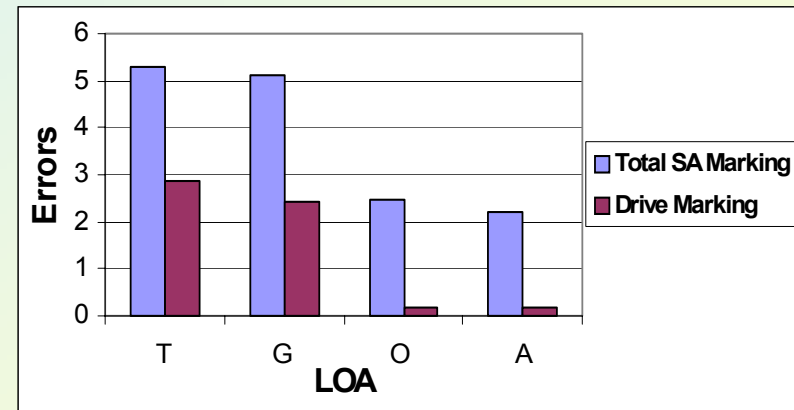
- Participants also rated higher LOAs as less difficult to maintain SA and ranked higher LOAs as better for SA.
 - Most likely due to having extra time to concentrate on SA as control eases
- Conclusion is also backed up by participants estimates of concentration and subjective responses.
 - Subjective responses indicate higher LOAs enabled more time to concentrate on SA.
 - Estimated lower overall level of concentration in higher LOAs
 - Mainly due to a lower estimation of time spent on robot control.
 - A large portion of this freed time was devoted to increasing the time spent on SA instead of spent idly.
 - This indicates that and if time was not an issue participants would have spent more time on SA by sacrificing speed in lower LOAs
- Overall conclusion: reducing the control demands of an operator has a positive effect on operator SA
 - mainly for memory tasks with only a marginal effect on navigation.





LOA Results (cont)

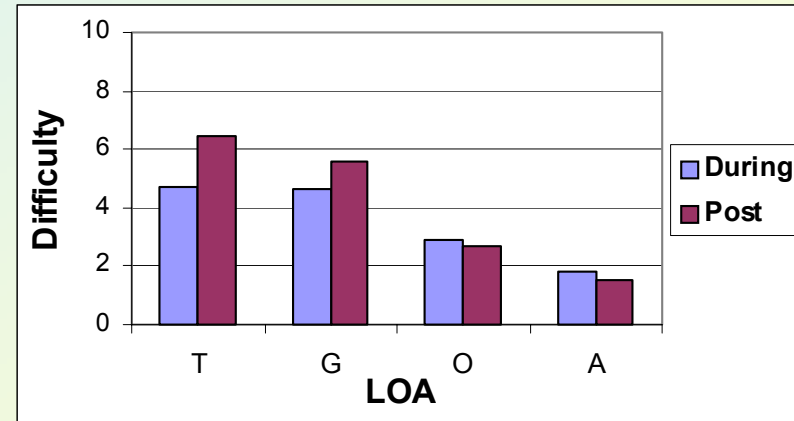
- A large portion of the increase in total SA marking mistakes at low LOAs is for the most part due to the increase in driving error marking mistakes that were made in lower LOAs.
 - Probably due in large part to the major increase in drive errors made at lower LOAs
 - Hence decrease in total SA marking mistakes is not entirely due to increased SA in higher LOAs (detracts from previous conclusion).
 - However with varying latency more R/R-M errors were found in guarded teleoperation than in higher LOAs, and the combined analysis revealed an increase in large P-M errors as LD increases in low LOAs but not in high LOAs.
 - This indicates that increasing the LOA does indeed help with remembering the route of the robot and its effect on total SA marking mistakes is not entirely due to the increase in driving errors made at lower LOAs.





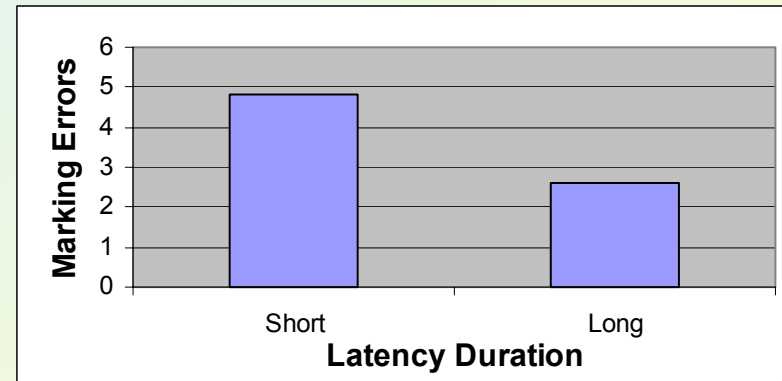
LOA Results (cont)

- In experiment 2 when participants were asked to rate the difficulty in maintaining SA both after each run and again at the conclusion of the experiment.
 - The estimated difficulty was much larger post experiment than during for low LOAs but not high LOAs.
 - This indicates that subjects remembered the difference between LOAs as being larger than their initial estimates, and after being exposed to all LOAs had an even larger preference for high LOAs when trying to maintain SA.



Latency Duration Results

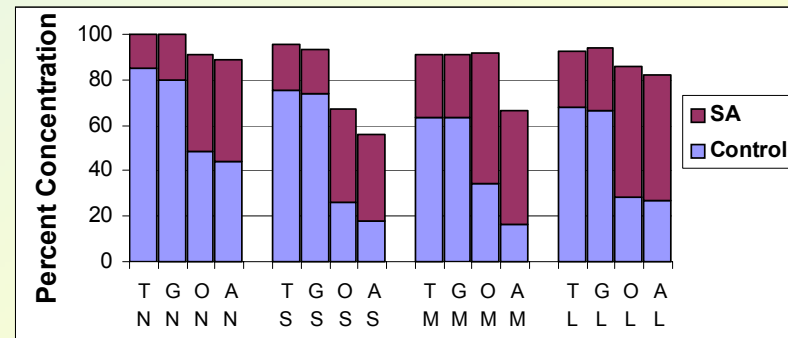
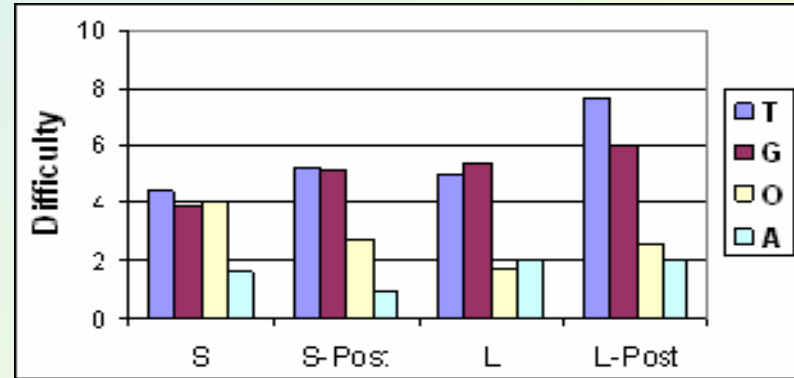
- In general navigation and SA marking mistakes did not increase as latency duration increased and in many cases actually decreased
 - Increasing latency duration did not cause controllers to get lost more often along the route
 - Increasing latency duration did not impair the ability to remember the route and where mistakes were made
 - Most likely due to subjects slowing down due to increased control difficulty or switching to a move-and-wait control strategy, both of which allow more time for SA.





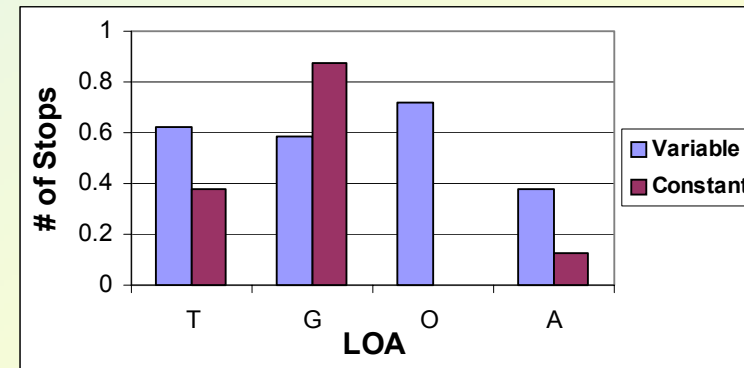
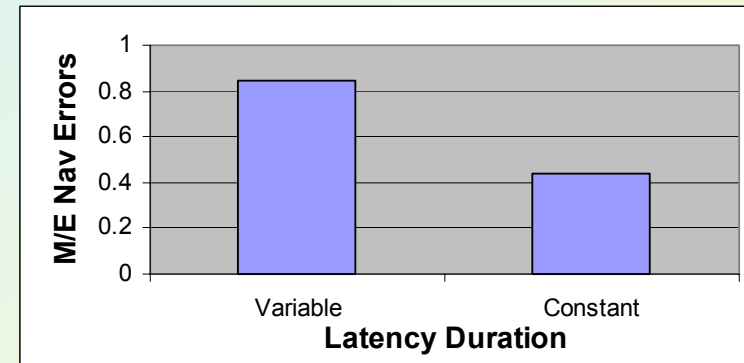
Latency Duration Results (cont)

- Lag duration did not significantly effect SA rankings
- No major differences in perceived difficulty in maintaining SA as duration increases
 - Under variable latency the difficulty ratings did show a larger difference between LOAs in the long latency condition than in short.
 - Effect was amplified in post experiment ratings.
 - With long varying latency the O and A LOAs were ranked equally.
 - This indicates that participants felt increased LOA was beneficial for maintaining SA when dealing with varying communication latency, but that once the duration reaches a certain point increasing the LOA further does not aid the operator.
- Estimated total concentration was smaller in high LOAs with a short latency duration.
 - As LD increased an increasing amount of this idle time was estimated to be used on SA.
- Overall conclusion: increased latency duration made SA slightly more difficult to maintain, however this can be accommodated by slowing down.
 - Increasing the LOA up to a point was at least perceived to help as the duration of the latency increased



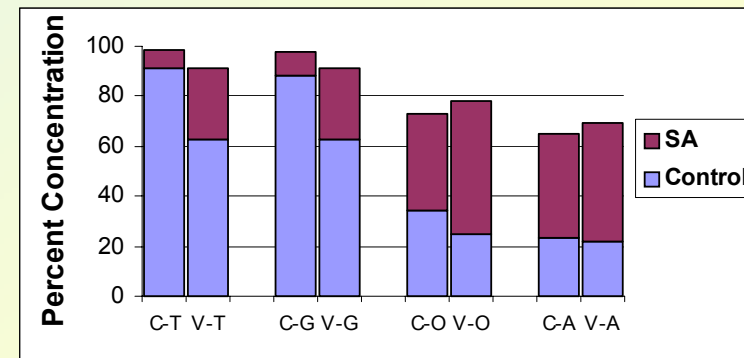
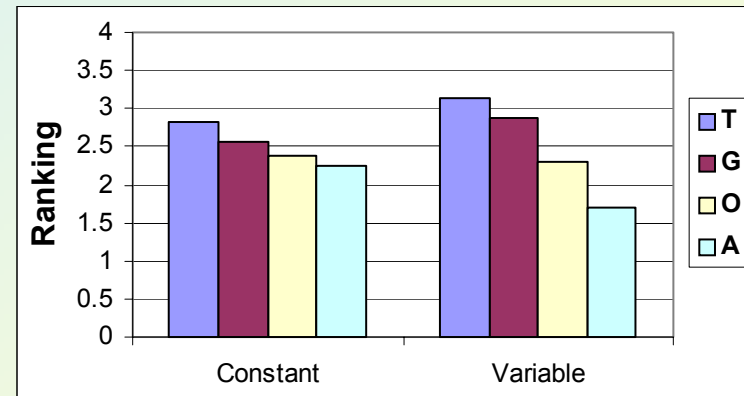
Lag Variability Results

- No effects on SA marking mistakes were seen
- Two effects on navigation errors neared significance
 - Varying latency made it somewhat more difficult to locate reconnaissance and mission end points.
 - Constant latency increased the number of stoppages due to becoming lost over that with varying latency in lower LOAs.
 - This is most likely due to users becoming lost easier when control is more constant
 - Participants probably have not switched to a move-and-wait strategy and hence are not frequently task switching from control to SA



Lag Variability Results (cont)

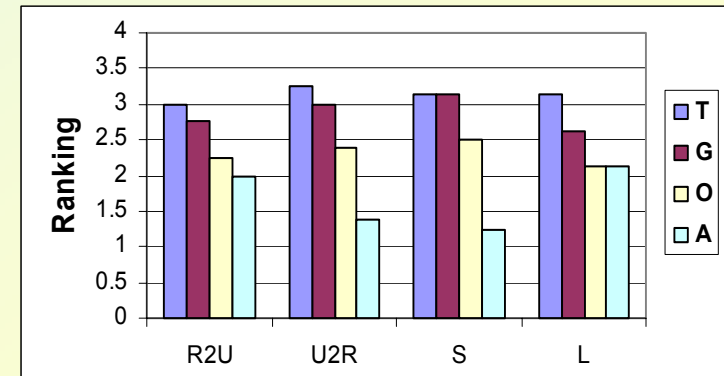
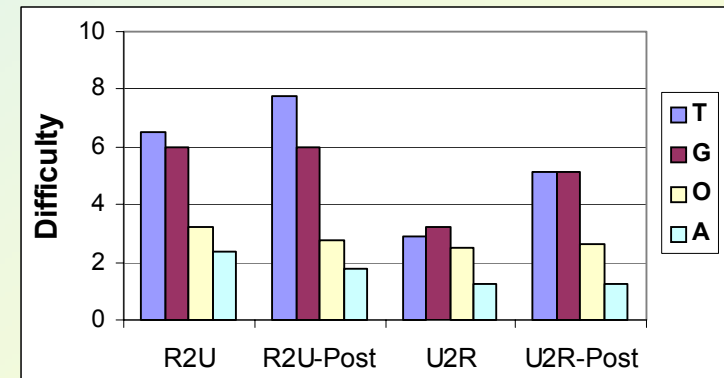
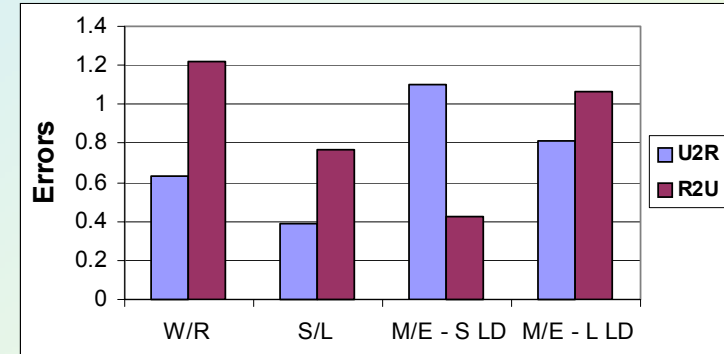
- No significant difference in perceived difficulty ratings or rankings for constant vs. variable across LOAs
 - However the difference between rankings of LOAs was larger with variable than constant latency.
- Concentration estimates of SA were larger for variable than constant lag particularly in lower LOAs.
 - However the total concentration estimation was not larger for variable latency, and accordingly less time was estimated for control.
 - This is counter intuitive as varying the latency duration should not ease control.
 - Most likely due to slowing down under variable latency
- Overall conclusion: variable latency made SA slightly more difficult to maintain for navigation but not for memory tasks.
 - However this again was most likely offset by slowing down or switching to a move-and-wait strategy under variable latency
 - Increasing the LOA was also helpful in decreasing both the perceived and measured effect.





Lag Direction Results

- No effects on SA marking mistakes
- Several effects of navigation errors neared significance
 - Fewer W/R mistakes made in U2R than R2U
 - Less M/E errors in R2U with S LD.
 - Fewer S/L mistakes in U2R than R2U
- Difficulty maintaining SA rating was much larger for R2U than U2R
 - Effect was minimized as LOA increased.
- SA Ranking - effect of higher LOAs ranking better was more pronounced in U2R than R2U
 - Increasing LOA is more helpful when control signals are delayed
- No significant difference in perceived % time spent on control vs. SA for R2U vs. U2R





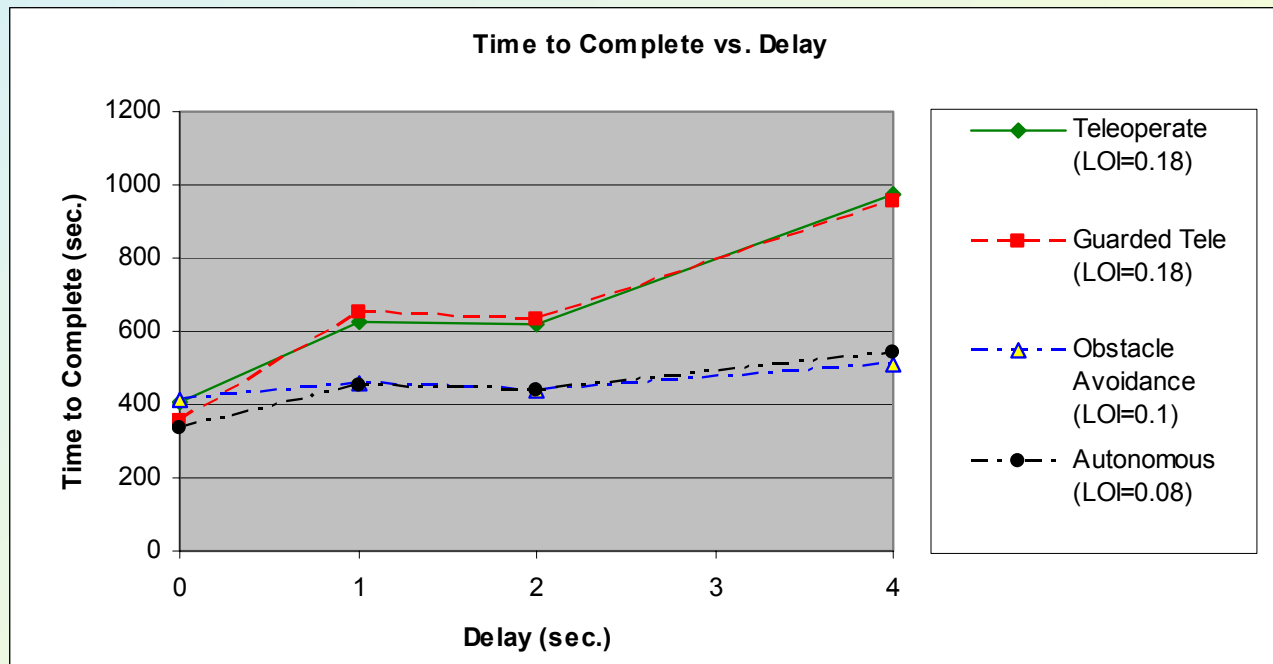
Lag Direction Results (cont)

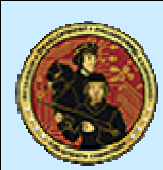


- Overall Conclusion: Maintaining SA is slightly harder when the feedback coming from the robot is delayed than when the control signals going to the robot are delayed. This effect was seen for navigation but not for memory tasks.
 - This is most likely due to a slight advantage of getting real-time feedback of the robots position and view of the world.
 - However this advantage is very small since in reality the direction of the delay is transparent to the user
 - Increasing the LOA is at least thought by the participants to lessen this effect.

Applying Results to Other Robots and Tasks

- Level Of Interaction (LOI)
 - Average number of control movements made by the operator per minute for a given task
 - Changes with task difficulty, speed of movement, and LOA
 - Similar to that described by Olsen and Goodrich





Paper Covering SA Results



- Almost complete with rough draft
- Email me at jluck@maad.com if you are interested and I will send you the paper as soon as it is finished.



Performance Results

- A paper summarizing the performance results for both experiments was presented at the 2006 Human Robot Interaction Conference
 - Luck, J.P., Allender, L., and McDermott, P.L., “An Investigation of Real World Control of Robotic Assets under Communication Latency”, Proceedings of the 1st Annual Conference on Human-Robot Interaction, Salt Lake City, UT, 2006
- Interaction between operator SA and control performance will be very interesting
 - Does operator SA decrease in conditions where performance increases?
 - What are the tradeoffs?
 - Will hopefully submit a paper covering this to the IEEE Intelligent Systems - Special Issue on Interacting with Autonomy



Future Experiments

- Investigate display options for tradeoff between limiting framerate and resolution in reduced bandwidth applications
 - In many situations vehicle control will not be as sensitive to video resolution as it is to framerate.
 - The opposite for extracting information from the video stream.
- Investigate different display options :
 - Provide user ability to adjust between framerate vs. resolution in real-time
 - Cross-adaptation approaches for framerate-resolution tradeoff adjustment: direct operator control, explicit goal-oriented task sequences, or current UGV operating conditions (e.g. speed)
 - Foveated display (high resolution focal point with degrading peripheral vision)
 - High resolution forward view with low resolution side-views

