



Passenger Experience of Simulated Urban Air Mobility Ride Quality: Responses to Large-Scale Motion

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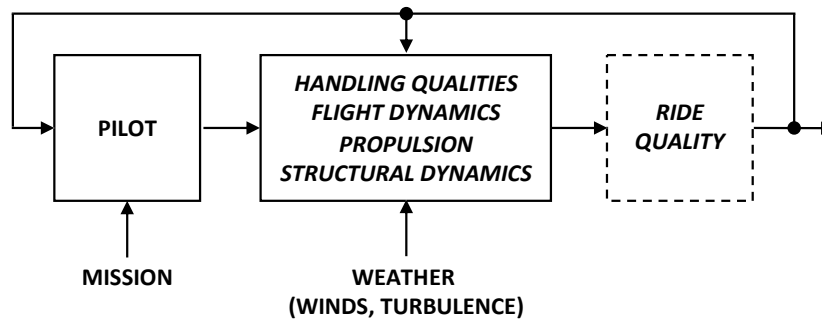
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Ride Quality

Pilot Handling Qualities → Ride Quality

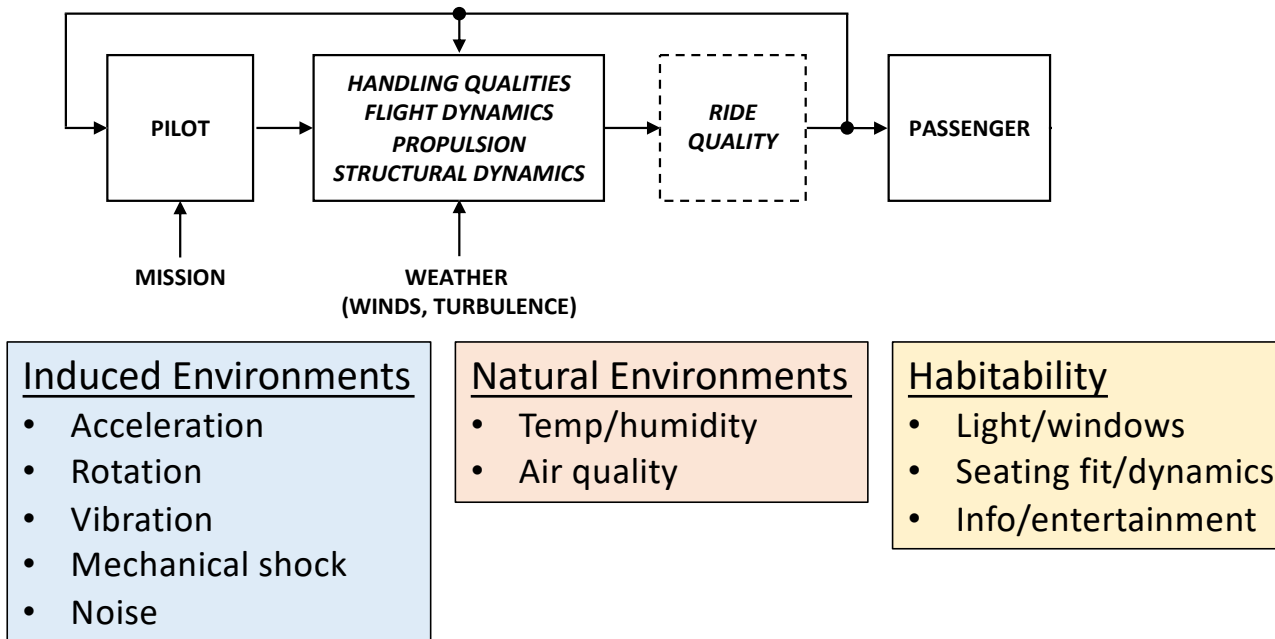


Induced Environments

- Acceleration
- Rotation
- Vibration
- Mechanical shock
- Noise

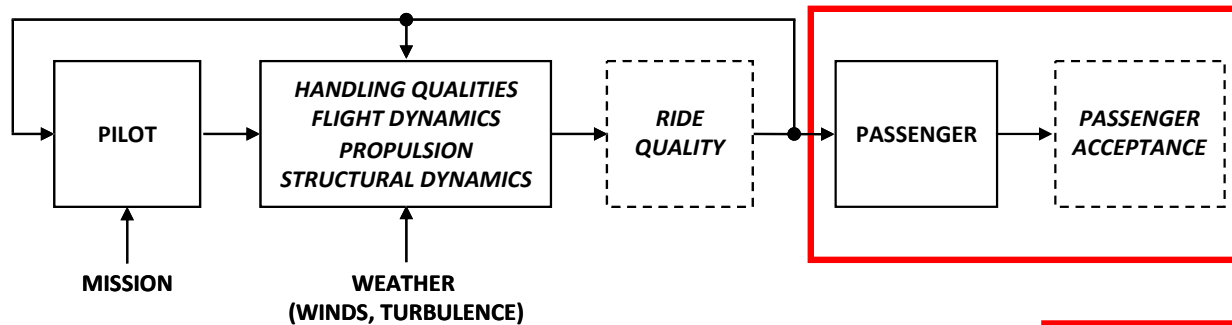
Passenger Experience of Ride Quality (Comfort)

Pilot Handling Qualities → Ride Quality



Passenger Acceptance of Ride Quality

Pilot Handling Qualities → Ride Quality → Passenger Acceptance



Passenger Acceptance = $f(\text{Comfort, Cost, Convenience})$

Comfort

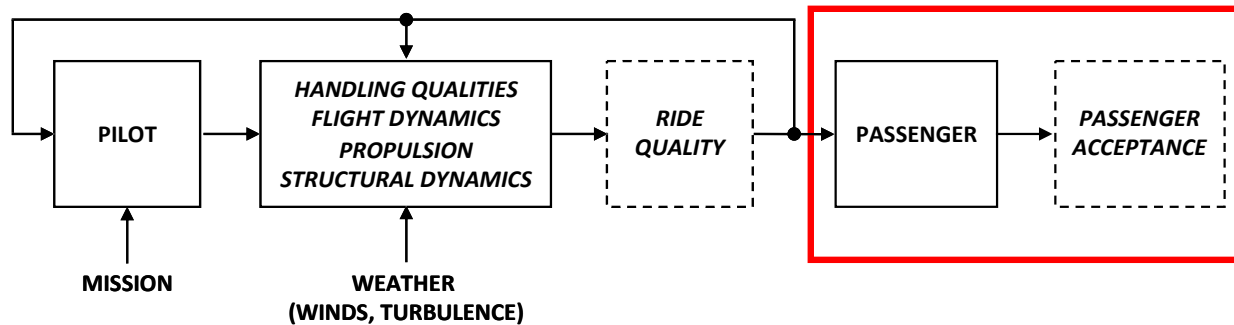
- **Motion**
- Vibration
- Noise
- Thermal
- Atmospheric
- Ergonomic
- Social

Performance

- **Visual**
- **Manual**
- Hearing
- Speech

Passenger Acceptance of Ride Quality

Pilot Handling Qualities → Ride Quality → **Passenger Acceptance**



Passenger Acceptance = $f(\text{Comfort, Cost, Convenience})$

NASA Passenger Ride Quality research program 1970s-1980s

- Langley Research Center in-house and external grants
- Focused largely on ***fixed-wing commercial passenger transport***
- Mainly ground-simulator studies for ***vibration**** and ***noise***
- Some inflight ***motion*** studies

Comfort

- ***Motion***
- ***Vibration***
- ***Noise***
- Thermal
- Atmospheric
- Ergonomic
- Social

*Foundational data underpin current ISO 2631-1 Standard for whole-body vibration health and comfort

GOALS (for this study):

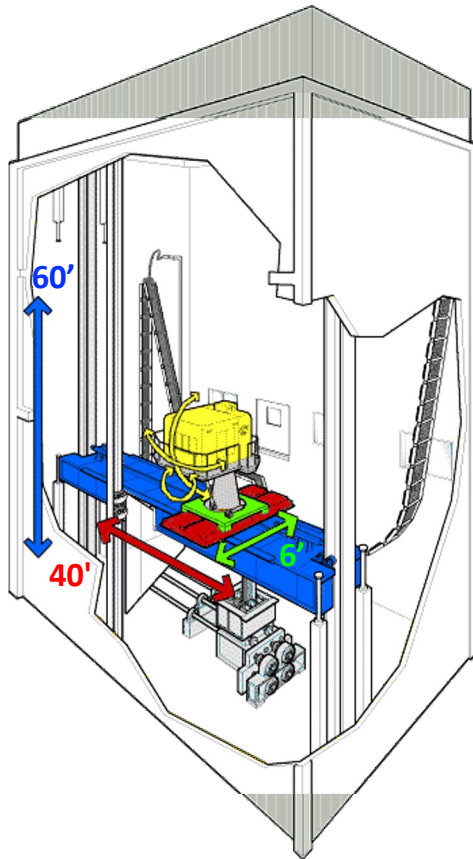
- Conduct a pathfinder ground-based simulator study of passenger response to ***Urban Air Mobility (UAM)*** vehicle motion
- Examine the utility of a selection of subjective and objective methods (software and hardware) for passenger ride quality assessment

PLAN (for this talk):

- ✓ Background
- Flight motion stimuli
- Equipment and methods
- Study design
- Results and discussion

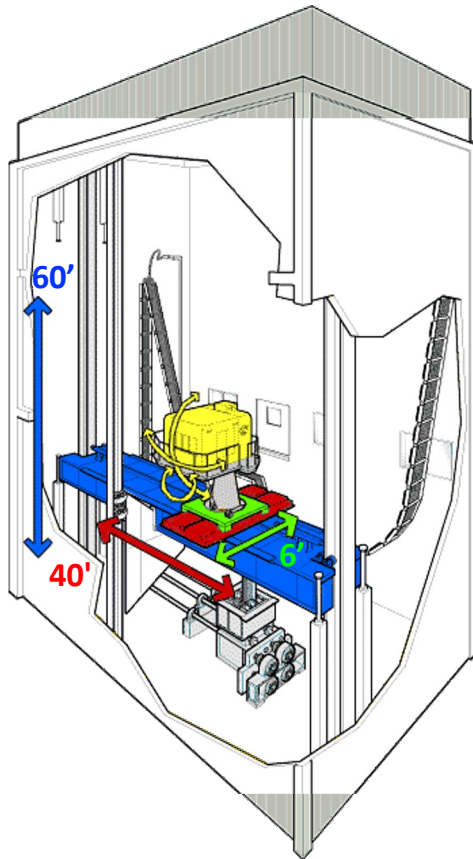
Facility and Simulation Model: Target of Opportunity

**Vertical Motion Simulator (VMS)
at NASA Ames Research Center**



Facility and Simulation Model: Target of Opportunity

Vertical Motion Simulator (VMS)
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Quadrotor NASA Reference Design



- Follow an immediately preceding pilot-in-the-loop (Withrow-Maser et al, 2022; Aires et al. 2022) handling qualities (HQ) study of rotor speed (i.e., **RPM**) and blade pitch (i.e., **Collective**, or **COL**) controlled eVTOL versions of the quadrotor
 - VMS simulation models for **RPM** and **COL** quadrotor were fully developed beforehand

Simulation Flight Trajectories

Prior to solo passenger testing, NASA research test pilot (with one investigator on board) flew simulated trajectories over San Francisco on the VMS.

- **COL** and **RPM** configurations at different Dryden turbulence model (McFarland & Duisenberg, 1995) intensity settings.
- Full-state trajectory recordings for VMS playback **without** pilot on board.

The same turbulence scale factor selected for our study's two (i.e., **COL** and **RPM**) flight conditions.

- Despite turbulence factor being 2.5x higher at cruising altitude than Withrow-Maser et al. and Aires et al.'s HQ study, **COL**, due to its higher dynamic bandwidth rejection of heave (vertical) motion, is notably smoother than **RPM** condition.

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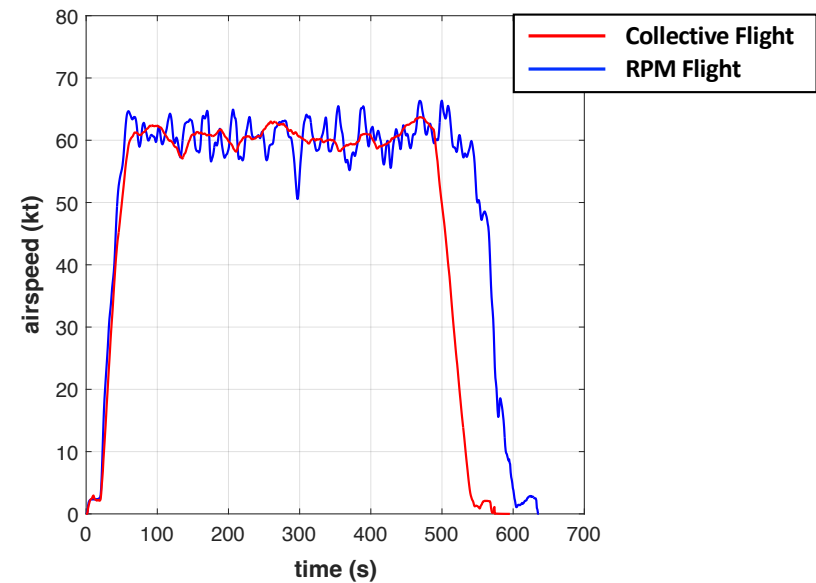
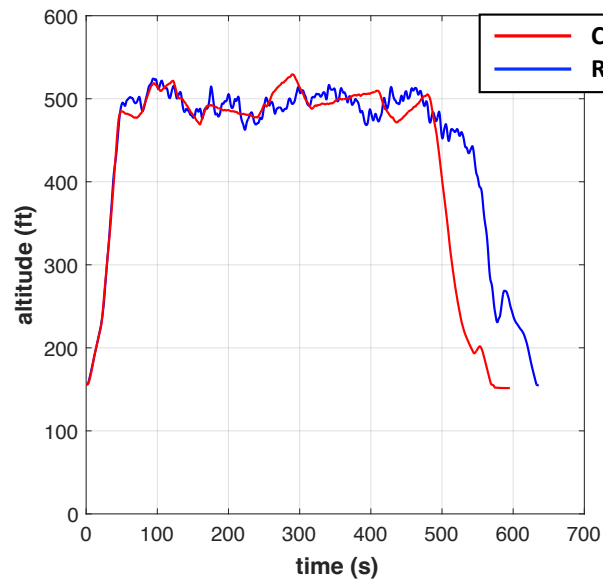
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RPM and Collective Flight Paths: Vertical and Tangential Motion

Modeled Quadrotor Cabin Motion



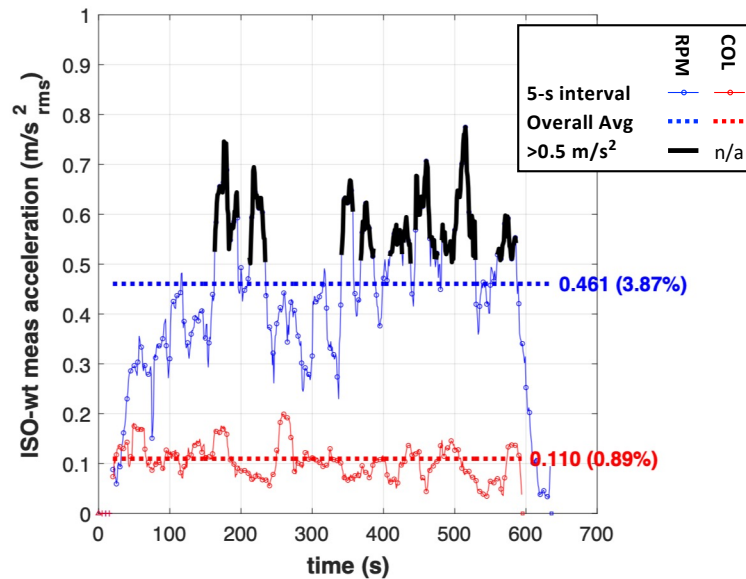
- Cruising altitude (500ft) and speed (60kt) reached at 50-60sec
- Descent to vertiport landing begins at ~480 sec for COL flight and ~540 sec for RPM flight

Difference in roughness associated with RPM vehicle's phugoid and roll motion

RPM and Collective Flight Paths: Roughness Severity

Measured VMS Cabin Vertical Acceleration

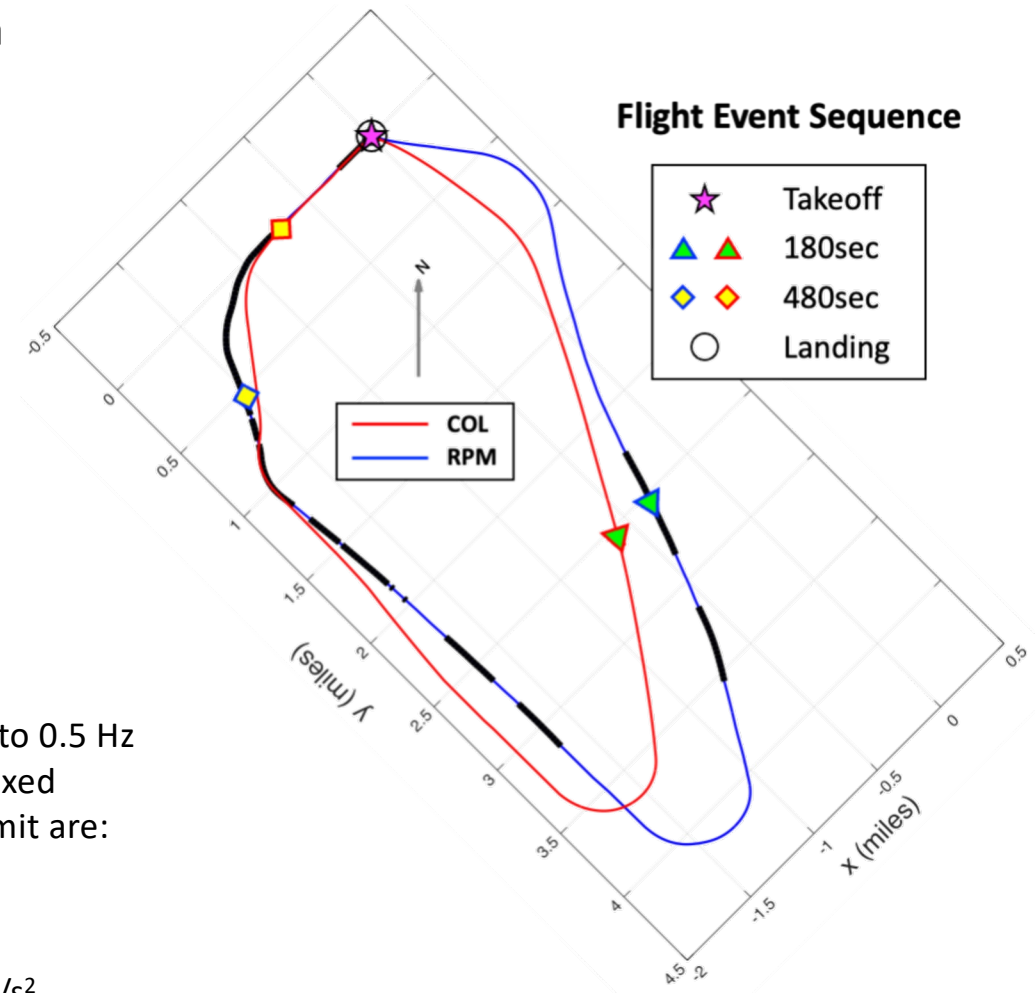
Motion Sickness Risk (Emesis Likelihood)



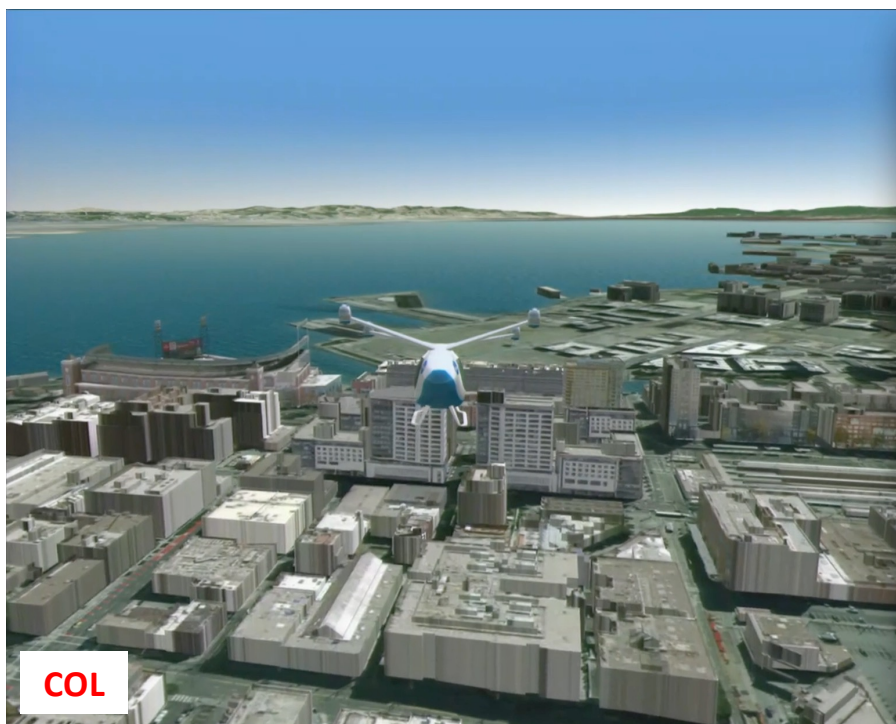
Following ISO 2631-1(1997) Annex-D for W_f -weighted 0.1 to 0.5 Hz vertical acceleration, the predicted likelihoods* that a “mixed population of unadapted male and female adults” will vomit are:

- **RPM** profile: 3.9% (1 in 25)
- **COL** profile: 0.9% (1 in 111)

*Note: validated for 20-360 minutes for overall rms avg $\leq 0.5 \text{ m/s}^2$



RPM and Collective Motion: “Chase Plane” Video



2X Speed

Experimenter-Provided Hardware/Software

iPad Air (4th generation)

PVT+ app developed in-house (available free at Apple App Store)

- Psychomotor Vigilance Test (PVT): a reaction time task → **DEMANDS TOTAL VISUAL ATTENTION**
 - Demographics
 - Short-form Motion Sickness Susceptibility Questionnaire (MSSQ)—(Golding, 2006)
 - Severity ratings of childhood and recent (10yr) experience on various conveyances
 - Simulator Sickness Questionnaire (SSQ)—(Kennedy et al., 1993)
 - Severity ratings of various motion sickness symptoms
- NASA-TLX app developed in-house (available free at Apple App Store)

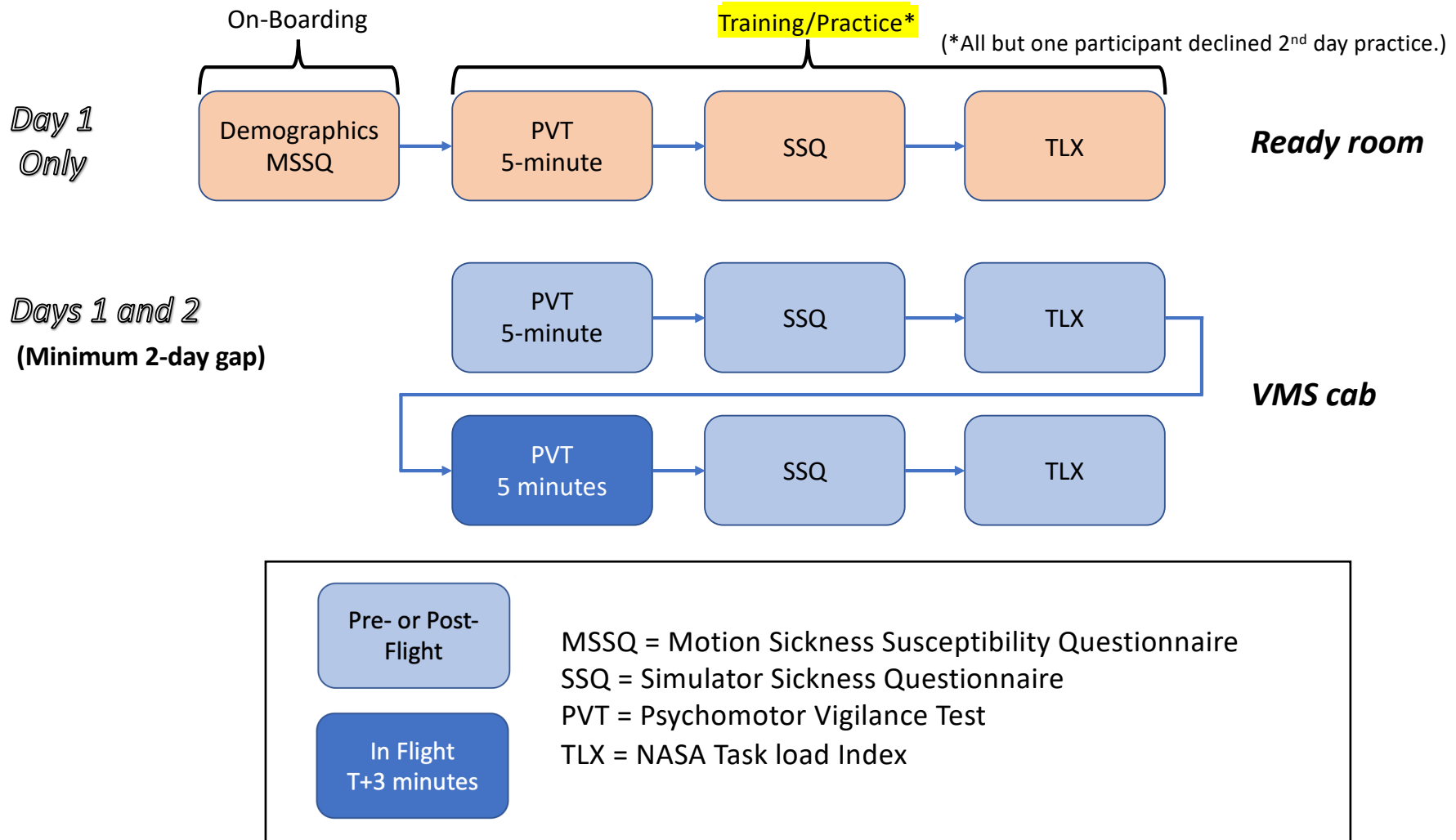
Equivital EQ02 (chest-worn system)

- Two-lead electrocardiogram (ECG)
- Heart and respiration rates
- Chest skin temperature
- Triaxial acceleration

Empatica E4 (wrist-worn system)

- Electrodermal activity (EDA)
- Blood volume pulse (BVP)
- Wrist skin temperature
- Triaxial acceleration

Participant Task Workflow



Participation Criteria and Demographics

Inclusion/Exclusion Criteria

- NASA-Ames badged personnel
- Naïve to VMS
- Non-pilots
- Abide by Covid regulations

Study Design

- Based on hypothesized sign-test outcome: $SSQ(\text{RPM}) > SSQ(\text{COL})$, power analysis ($\alpha < 0.05$ for $1 - \beta = 0.8$) $\rightarrow$ min 23 participants
- Plus one more participant to **counterbalance** between groups for **RPM/COL** order

Participant Demographics

- 25 were consented; 23 started and completed the protocol
 - 12 assigned to **COL** first day (**Cfirst** group);
 - 11 to **RPM** first day (**Rfirst** group)
- 19M/4F; age 20-67yr (median 38yr; mean 42.8yr)

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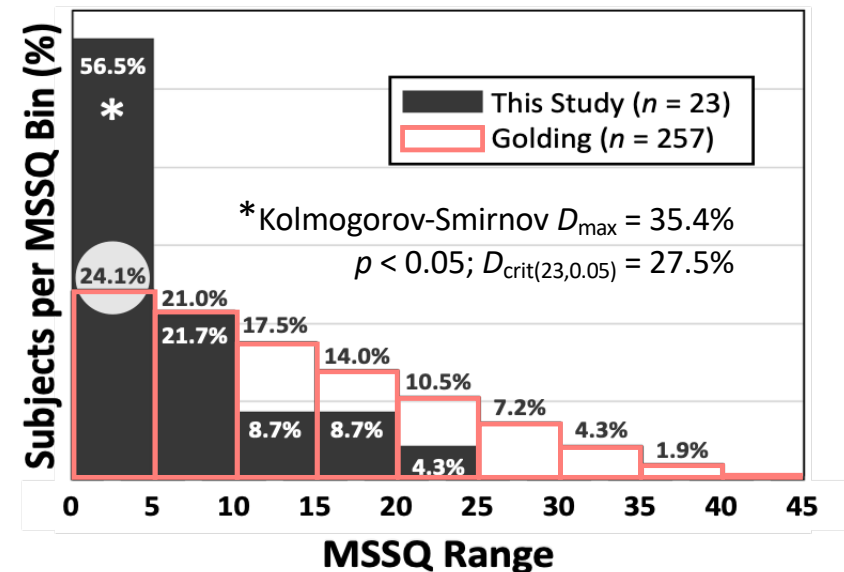
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- MSSQ responses indicate lower susceptibility (median total score = 4.0) than Golding's validation pool (median = 11.3)*

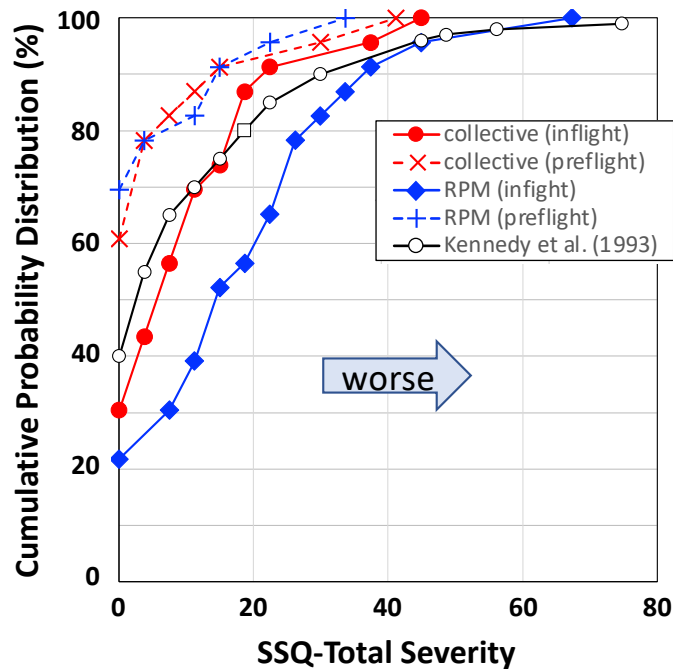
Motion Sickness Susceptibility vs Golding's Canonical Population



- 13 (of 23) self-selected volunteers self-scored in the lowest [0-5] bin
- No significant difference between **Cfirst**/**Rfirst** order groups

Subjective Self Report: Simulator Sickness Questionnaire (SSQ-Total Severity)

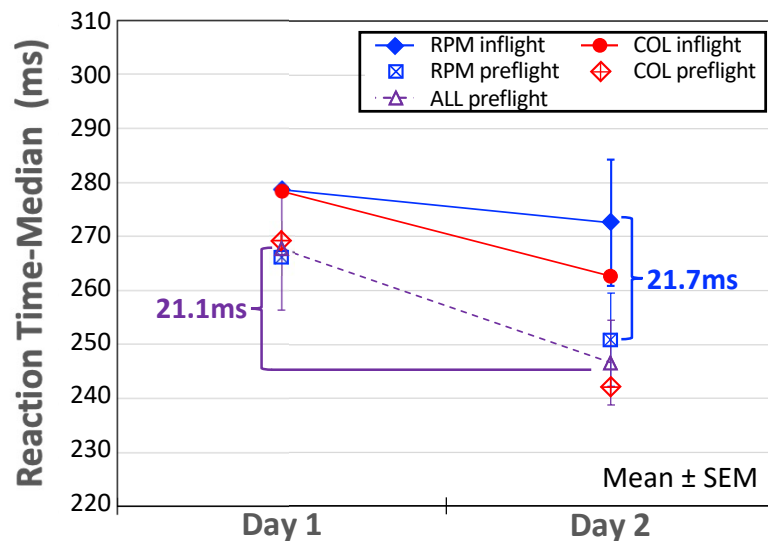
- No significant difference between **Cfirst** and **Rfirst** groups:
COL: Mann-Whitney $U = 54$, $z = 0.752$, $p_{2\text{-tail}} > 0.4$
RPM: Mann-Whitney $U = 59.5$, $z = 0.403$, $p_{2\text{-tail}} > 0.6$
- Inflight **RPM** (median 14.96) > inflight **COL** (median 7.48)
 Wilcoxon matched-pair sign-rank ($T^+ = 172$, $n = 20$, $p < 0.0053$)**



Comparisons vs Kennedy et al.'s ($N = 1100+$) SSQ-TS Calibration Distribution

Flight Condition		Distribution Difference
Inflight	COL	$\chi^2 = 1.167$, $df = 2$, $p = 0.56$ (ns)
	RPM	$\chi^2 = 21.78$, $df = 2$, $p < 0.00002$
Preflight	COL	$\chi^2 = 4.174$, $df = 1$, $p < 0.05$
	RPM	$\chi^2 = 8.377$, $df = 1$, $p < 0.005$

Objective Task Performance: Psychomotor Vigilance Test (PVT) Learning



Main effect: Preflight/inflight **COL/RPM** condition
 $(F_{2,2,45.8} = 6.639, p < 0.003)$

Interaction: **COL/RPM** X **Cfirst/Rfirst** group
 $(F_{2,2,45.8} = 6.743, p < 0.003)$

General Learning/Training trend in reaction times (RT)

21.1ms (7.9%) Day 1 to Day 2 *preflight* improvement
 combined across **Cfirst** + **Rfirst** ($t_{22} = 3.737, p_{2\text{-tail}} < 0.0011$)

Significant increase in Day 2 preflight-to-inflight **RPM** RT

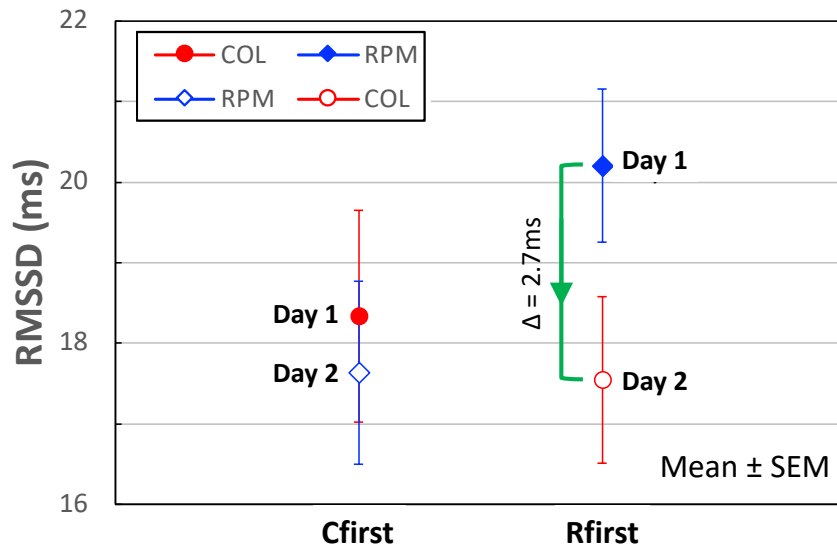
21.7ms (8.5%) for **Cfirst** ($t_{11} = 4.678, p_{2\text{-tail}} < 0.0007$)



Rougher **RPM** flight impedes task improvement
 (i.e., learning/training) on 2nd flight

Physiological Metrics: Passenger Stress-Heart Rate Variability

- Heart Rate Variability (HRV) is an indicator of Parasympathetic Nervous System (PNS) tone — inversely correlated with recovery from stress or, effectively, “relaxation”
- Focus on Root Mean Square of Successive Differences (RMSSD) between adjacent heartbeat intervals



Log(RMSDD) Interaction: **COL/RPM** X **Cfirst/Rfirst**
($F_{2.1,43.7} = 4.629, p < 0.014$)

Significant drop in Day 2 Log(RMSDD) for Rfirst group

−2.7ms (−13%) ($t_{32} = 4.678, p_{2\text{-tail}} < 0.001$)

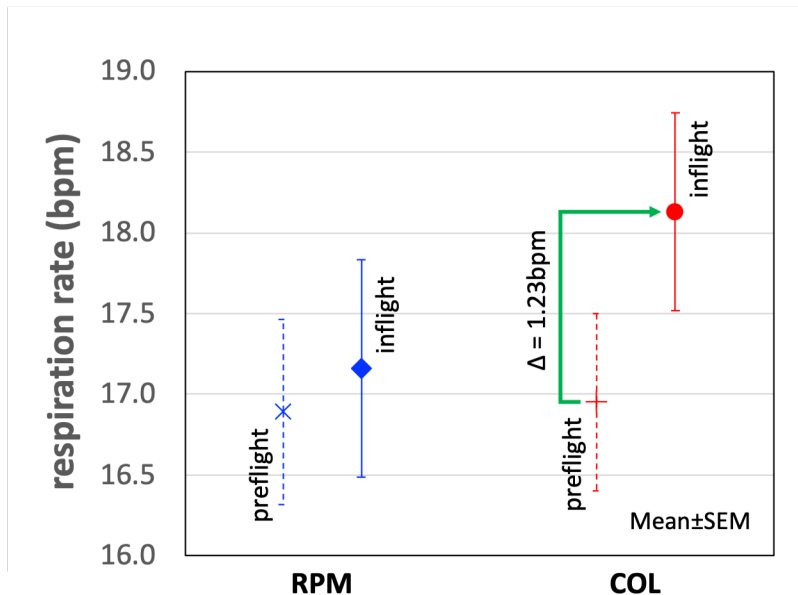
Rfirst's statistically significant drop in HRV indicates decreased relaxation on more benign 2nd (**COL**) flight; **Cfirst** did not change significantly between flights.



Potential importance of first flight experience on passenger acceptance.

Physiological Metrics: Passenger Stress-Breathing Rate

- Respiration rate (in breaths per minute, or bpm) is inversely correlated with stress.



Main effect: Preflight/inflight **COL**/**RPM** condition
($F_{2,1,44.4} = 3.676$, $p < 0.03$)

Significant preflight to inflight rise in respiration rate for **COL** flight:

1.2bpm (7.2%) ($t_{23} = 3.446$, $p_{2\text{-tail}} < 0.0023$)

The rise in respiration rate indicates diminished stress levels once the **COL** flight starts. There is no significant preflight to inflight change for the **RPM** condition.

Participants' anticipatory preflight stress dissipated once a smooth (e.g., **COL**) flight is experienced. Rougher, e.g., **RPM** condition does not offer comparable relief.

Summary-I

Empirical SSQ scores (our study's main dependent variable) aligned with ISO 2631-1 analytic predictions of "RPM > COL > preflight" motion sickness severity ranking.

- Demonstrated utility of SSQ (or SSQ-like) as a viable tool for subjective examination of passenger acceptance of Ride Quality (RQ)—despite MSSQ results indicating our participant's lower motion sickness predisposition.
- Corroborated that, from passenger perspective, RQ is degraded under RPM control (as was seen in preceding UAM pilot HQ testing).

Summary-II

Intriguing objective effects, though more nuanced, were detected. The following observations indicate potential UAM passenger acceptance impacts that warrant further investigation:

1. Rougher flight hampered learning for at least one type of visual-manual task;
2. Rougher first flight primed participants to be less relaxed for their second flight, even when that second flight is more benign;
3. Anticipatory preflight stress was relieved by a smooth flight experience.

Further Work

Future studies would benefit from:

- More challenging and more representative flight profiles enhanced with flight-like vibration and larger out-the-window views;
- Recruiting participant groups with better gender balance and who have broader motion sickness predisposition representation;
- Different inflight passenger tasks as well as better physiological instrumentation.

Acknowledgements

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Our thanks to

- VMS staff, especially Matt Blanken and Darren Benn, the engineers at the console
- Gordon Hardy, NASA Ames research test pilot
- Dr. Ralph Pelligra, NASA Ames medical monitor
- Kenji Kato for PVT+ app development
- Carlos Malpica for UAM domain insight
- Most of all, the study's 23 participants

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