

Urban Air Mobility Passenger Discomfort Evaluations of Sudden Heave Motion in a Virtual Reality Motion-Base Simulator

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ABSTRACT

Small, highly maneuverable Urban Air Mobility (UAM) air taxis might exhibit motions during hover and low-speed flight that are unfamiliar to many passengers, and for which there are no established guidelines to predict passenger comfort. Researchers performed a study in the Armstrong Virtual Reality Passenger Ride Quality Laboratory to identify relationships between sudden motion characteristics and UAM passenger comfort and acceptance. Twenty-three volunteer test subjects from the Armstrong workforce each completed a 15-minute experience as a passenger in a virtual air taxi simulation. Subjects evaluated a series of flight maneuvers with varying levels of sudden motion using a five-point rating scale and indicated which motion(s) they found uncomfortable. Researchers then administered a post-test questionnaire to relate the passengers' ratings to their willingness to fly on a real air taxi with similar levels of motion. The study results relate peak heave acceleration and jerk to passenger acceptance.

NOTATION

a_z^m	Heave Acceleration of the Aircraft Model
$\dot{a}_z^m$	Heave Jerk of the Aircraft Model
$a_z^{p'}$	Intermediate Heave Acceleration of the Platform
a_z^p	Final Heave Acceleration of the Platform
AFRC	Armstrong Flight Research Center
°C	Degrees Celsius
C_{RQ}	Ride Quality Rating
CG	Center of Gravity
deg	Degrees
ft	Feet
°F	Degrees Fahrenheit
FP	Flight Path
HQ	Handling Qualities
in	Inches
J ³ ERQ	Jerking, Jostling, and Jolting Effects on Ride Quality
kts	Knots
lb	pounds
m	Meters
min	Minutes
MTE	Mission Task Element
n	Number of Participants
NASA	National Aeronautics and Space Administration
O	Filter Output
p	Probability
P_{DISC}	Passenger Discomfort, percent
PI	Principal Investigator
R	Correlation Coefficient
R^2	Coefficient of Determination
RMS	Root Mean Square
RQ	Ride Quality

RQL	Virtual Reality Passenger Ride Quality Laboratory
RVLT	Revolutionary Vertical Lift Technology
s	Seconds
s	Laplace Operator
SSQ	Simulator Sickness Questionnaire
UAM	Urban Air Mobility
US	United States
VMS	Vertical Motion Simulator
VR	Virtual Reality
α	Level of Significance

INTRODUCTION

The National Aeronautics and Space Administration (NASA) is investing in research to support an Urban Air Mobility (UAM) system that is safe, economical, and environmentally friendly. The UAM system is envisioned to open new markets, transporting people and goods to locations not supported by the current air transportation system (Ref. 1). Urban Air Mobility passenger operations will require advanced Vertical Take-Off and Landing (VTOL) vehicles that are safe, quiet, efficient, affordable, and that have acceptable passenger ride quality (RQ).

Ride Quality describes the effects of aircraft flight characteristics on the health, comfort, and performance of the occupant. Passenger discomfort is the degree to which the physical, mental, and emotional aspects of the flight experience are objectionable to the passenger. Psychophysical discomfort thresholds vary from person to person, so median subjective responses to different types and levels of stimuli must be established by way of a standardized process of evaluation and rating using human test subjects. Although

flight validation of passenger ride quality metrics will be required, laboratory and simulation testing can play an important role in their initial development (Refs. 2, 3).

Seminal ride quality research was conducted in the 1970s to quantify acceptable ride quality factors such as noise, vibration, and motion sickness (Refs. 4-9), with some limited consideration for other types of motion (Refs. 10-12). Urban Air Mobility aircraft with small cabins and large side and forward-facing windows will fly along highly dynamic routes near the ground and ground structures and through complex urban wind fields. These flights could produce unfamiliar combinations of physical and visual motion cues that passengers find uncomfortable or disconcerting. A better understanding of the relationship between these factors and passenger comfort will help vehicle developers, manufacturers, and operators provide an acceptable experience to UAM passengers.

This paper presents results from a study of volunteer test subjects in the Virtual Reality Passenger Ride Quality Laboratory (RQL) at the NASA Armstrong Flight Research Center (AFRC) (Edwards, California) in September and October of 2024. The study collected evaluations from twenty-three passengers for multiple levels of sudden motion in low-speed, low-altitude conditions representative of UAM vertiport operations.

This paper begins with a short description of the RQL used to conduct the study, followed by an overview of the study design. Motivation for the study and implementation details are presented along with a rationale for choosing the study factors and number of participants. Next, the study protocol is described, including recruitment and preparation of the participants and methodology for data collection. Following this, participants' ride quality and comfort ratings collected during virtual flights and follow-up questions on passenger acceptance of motion levels are presented. Next, the study results are discussed, including a statistical analysis of the significance of the results, an assessment of potential influencing factors and participant bias, acclimation during the experience, and adverse results. Conclusions and recommendations are summarized in the final section. Summaries of participant responses to two study questionnaires are provided as appendices at the end of the paper.

EXPERIMENTAL FACILITY

The RQL combines virtual reality (VR) visuals, six-degree-of-freedom motion, and stereo audio cues to provide a fully immersive passenger experience. The RQL, pictured in Figure 1, is a single-occupant, passenger (i.e., non-pilot) simulator located at the NASA AFRC. The RQL was approved for human operations in July 2024.

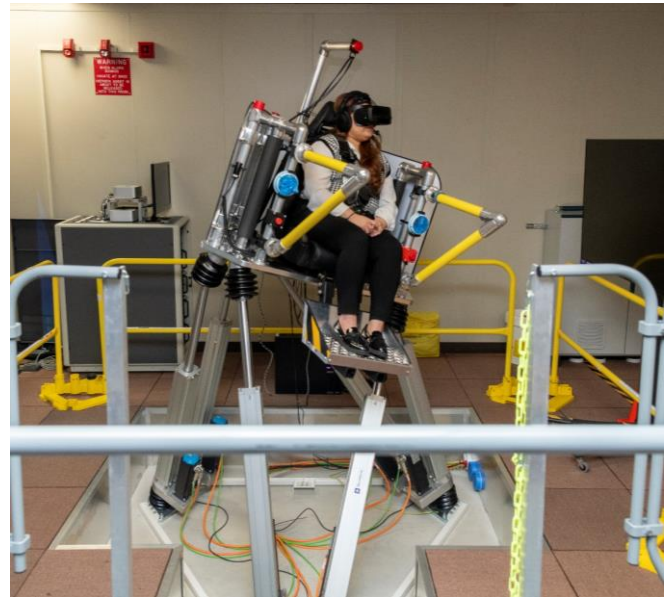


Figure 1. The NASA Virtual Reality Passenger Ride Quality Laboratory (RQL).

The virtual aircraft used for this study was a six-passenger (1,200-lb payload) Hexacopter, shown in Figure 2. This aircraft is a conceptual design developed by the NASA Revolutionary Vertical Lift Technology (RVLT) Project to be representative of an electric urban air taxi without exactly matching known industry designs (Ref. 13). The RQL exterior virtual environment is a high-resolution visual database of downtown San Francisco that has been modified to include a UAM vertiport on top of the parking garage at the intersection of 5th Street and Mission Street, also shown in Figure 2.



Figure 2. The NASA RVLT Hexacopter Conceptual Design at the Study Initial Position Next to the Vertiport in Virtual Reality.

The Hexacopter cabin interior design is shown in Figure 3. The simulator passenger occupies the right-hand forward seat in the cabin. A virtual screen displays information to the passenger. The screen is not interactive, and the passenger cannot see any part of himself or herself in the VR environment. Communication with the laboratory operators and study personnel is performed by way of a two-way audio headset.

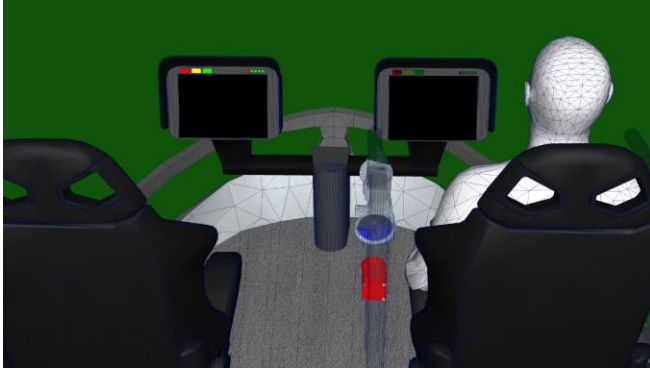


Figure 3. The Hexacopter Cabin Layout in Virtual Reality.

The passenger's left- and right-eye views out the front of the Hexacopter cabin at the study initial position are shown in Figure 4. Note the forward booms and rotors straight ahead and the vertiport off to the right. The visual environment is rendered as a clear day with the sun directly overhead.

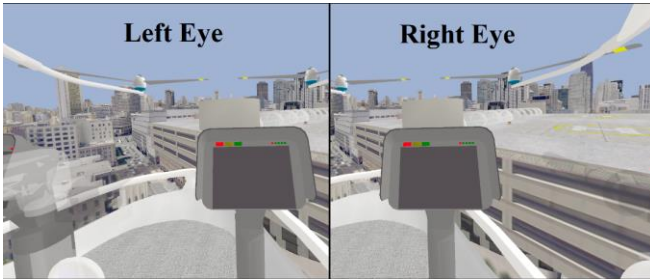


Figure 4. The Passenger Left-Eye and Right-Eye Views in Virtual Reality at the Study Initial Position.

The motion base of the RQL is an all-electric six-degree-of-freedom hexapod platform. The motion capabilities of the platform are listed in Table 1. Pre-recorded aircraft linear and rotational motion is transformed into a time series of hexapod pose commands using an offline classical linear washout (Ref. 14) motion cueing algorithm (MCA). The MCA can be tuned for specific flight motion to present the passenger with the best possible physical motion cues without exceeding the capabilities of the system.

Individual rotor sounds are presented to the passenger through an audio headset to mask the noise of the motion-base actuators and to improve the immersivity of the passenger experience. The rotor noise is modulated in pitch and volume based on rotor speed as reported by the vehicle simulation.

The sound produced by each of the six rotors is modeled using the built-in surround sound capability of a common open-source game engine. The point source of the sound of each rotor is the rotor hub location relative to the passenger's head. The rotor noise sound level in the passenger's headphones was set to be loud enough to mask the noise of the simulator motion base but not so loud as to prevent clear communication with the study team.

Table 1. RQL Motion Capabilities.

	Displacement	Velocity	Acceleration
Linear	m (ft)	m/s (ft/s)	m/s ² (ft/s ²)
Heave	±0.40 (1.3)	±1.0 (3.3)	±8 (26)
Sway	±0.46 (1.5)	±1.2 (3.9)	±8 (26)
Surge	±0.46 (1.5)	±1.2 (3.9)	±8 (26)
Rotational	deg	deg/s	deg/s ²
Roll	±30	±100	±800
Pitch	±30	±100	±800
aw	±40	±140	±1100

A padded, contoured racing seat, five-point harness, and footrest provide a level of comfort and physical restraint for the RQL passengers that is representative of a civilian urban air taxi. The RQL is at an altitude of approximately 2,350 ft and maintains a constant temperature of 70 °F (21 °C).

STUDY DESIGN AND IMPLEMENTATION

The title of the study was Jerking, Jostling, and Jolting Effects on Ride Quality (J³ERQ). Objectives of the study were to identify the levels of sudden motion that are distinguishable to the UAM passenger, and to identify relationships between motion characteristics, passenger comfort, and passenger acceptance. For the purposes of this study, the following informal, generalized definitions are used for categories of sudden motion.

Jerking: Jerking is a measure of the sharpness of the motion onset. Jerking is calculated as the maximum absolute value of the derivative of acceleration over the duration of interest.

Jostling: Distinct from vibration in that it is not continuous, jostling is prolonged, yet intermittent, motion. Jostling is calculated as the root mean square (RMS) of the acceleration over the duration of interest.

Jolting: Distinct from jostling in that it might only last for a few seconds and contain only a handful of peaks, jolting is sudden motion that is ephemeral. Jolting is calculated as the maximum absolute value of the acceleration over the duration of interest.

Study Motivation

A small sample of RQ ratings for the RVLTH Hexacopter in hover were obtained as part of a prior pilot handling qualities (HQ) experiment (Ref. 13) performed in the NASA Ames

Research Center (Moffett Field, California) Vertical Motion Simulator (VMS) in 2022. The RQ ratings were collected using the scale shown in Table 2.

Table 2. VMS Pilot Ride Quality Rating Scale.

Please rate the general experience of the ride as if you were a passenger.	
Overall RQ	Description
1	Polished / Glassy Comfortable ride without disturbances.
2	Mostly Smooth Representative of occasional light chop that does not appreciably change altitude or attitude.
3	Bumpy Representative of frequent light chop, moderate chop, or light turbulence.
4	Jolting Representative of moderate to severe turbulence.
5	Unacceptable Representative of severe or extreme turbulence where control may be impossible.

One of the evaluation maneuvers flown in the 2022 VMS experiment was the Hover Mission Task Element (MTE) from the ADS-33 Handling Qualities Requirements for Military Rotorcraft (Ref. 15). The Hover MTE, shown in Figure 5, requires the pilot to start from a stabilized hover at 20 ft (6.1 m) above ground level, reposition the aircraft along a 45-deg horizontal (constant altitude) path to the right at 6 to 10 kts, and then re-establish hover over a predetermined ground reference point. The VMS cabin configuration during these tests had two side-by-side seats, with the pilot in the right-hand seat offset from the aircraft model center of gravity (CG) by 1.8 ft (0.55 m) laterally and 3.1 ft (0.95 m) forward.

Four test pilots evaluated the RVLTH Hexacopter in the Hover MTE using a Translational Rate Command (TRC) flight control mode designed for Level 1 HQ. The aircraft model and MTE course were configured identically for all four pilots, and the maneuvers were flown with no simulated winds or turbulence. Each pilot completed three attempts, or runs, after which they gave their HQ and RQ ratings. The recorded RQ ratings ranged from 1: Polished / Glassy to 4: Jolting. Post-test analysis showed significant differences in flight dynamics between the runs, attributable to differences in pilot technique. Given the small sample size and large range of VMS pilot RQ ratings, it was decided that a larger follow-on study was needed to better understand the relationship between sudden motion and passenger acceptance. In support of the follow-on J³ERQ study, four of the pilot-flown VMS runs were selected to be replayed in the RQL for evaluation by volunteer passenger subjects.

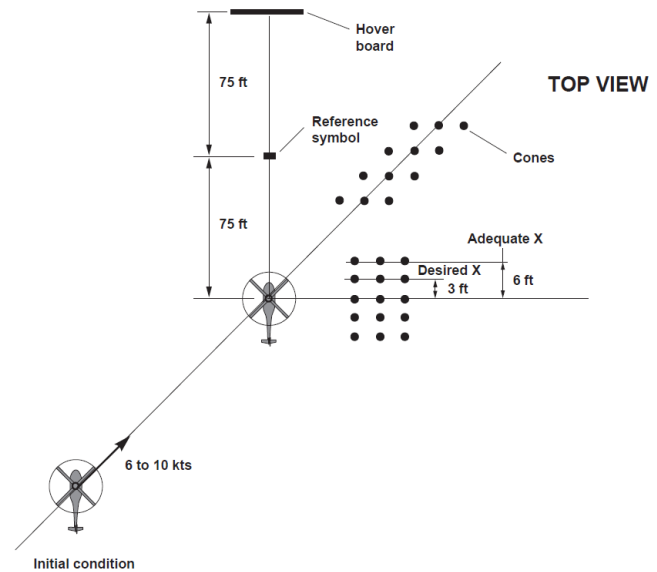


Figure 5. Hover Mission Task Element (Ref. 15).

Choice of Study Factors and Replay Runs

The VMS pilot who gave a RQ rating of 4 for the Hover MTE provided the following comments about the Hexacopter in TRC mode:

“Ride quality was definitely in the bumpy region, almost jolting. [...] the accelerations you’re feeling, the bump, the limiting, whatever it is that’s occurring, is painfully distracting.”

An analysis of the aircraft motion during the Hover MTE revealed that the most significant dynamics in the heave axis at the pilot station occurred during the deceleration from horizontal translation to a stabilized hover. Although the Hover MTE is performed at a constant altitude with almost no heave control inputs, horizontal maneuvering of the RVLTH Hexacopter is accomplished through changes in the pitch and roll attitude of the aircraft. Due to the offset of the pilot seat from the CG, these angular motions produce heave displacement at the pilot station. Heave acceleration during the deceleration phase of the maneuver was found to be significantly larger than accelerations in the other axes. Based on the maneuver analysis, and the pilot’s description of the ride quality, heave axis motion during the deceleration was identified as the stimulus most likely to correlate with the pilots’ RQ ratings.

The four VMS runs selected for the J³ERQ Study are listed in Table 3 along with the RMS heave acceleration (jostling), peak heave acceleration (jolting), and peak heave jerk (jerking) at the pilot station during the decelerate to hover portion of the MTE. The J³ERQ Study Run IDs were deliberately assigned to avoid alphabetical correlation with the ordering of stimuli magnitude.

Table 3. Pilot Station Heave Motion of VMS Runs Selected for the J³ERQ Study.

Run ID	RMS Accel., m/s ² (ft/s ²)	Peak Accel., m/s ² (ft/s ²)	Peak Jerk, m/s ³ (ft/s ³)
A	0.37 (1.22)	0.86 (2.81)	2.24 (7.36)
B	0.17 (0.55)	0.45 (1.47)	1.09 (3.56)
C	0.51 (1.68)	1.37 (4.48)	4.32 (14.2)
D	0.31 (1.00)	0.75 (2.46)	2.44 (8.00)

The values in Table 3 are also plotted in Figure 6. Run C has the maximum level and Run B has the minimum level of motion for all three measures of heave motion: jostling, jolting, and jerking. Runs A and D contain medium levels of motion, with Run A having a slightly higher level of jostling and jolting while Run D has a slightly higher level of jerking. The primary study factor was chosen to be peak heave acceleration (jolting) for the J³ERQ study because it is the simplest to calculate, can be directly measured, and is useful over a wide range of dynamic characteristics and durations. Peak heave jerk was chosen as a secondary study factor because of the different ordering of Runs A and D for that measure. The surge and sway accelerations for the four runs are not shown but follow a similar pattern, albeit with lower magnitude.

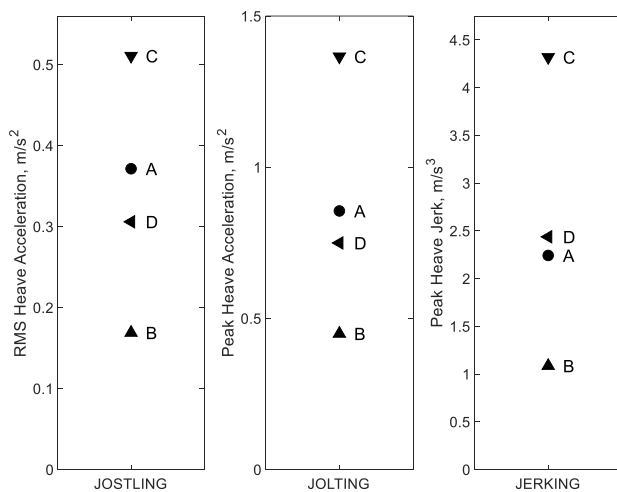


Figure 6. Pilot Station Heave Motion of VMS Runs Selected for the J³ERQ Study.

Figure 7 shows a time history comparison of the minimum (Run B) and maximum (Run C) heave responses at the pilot station. Note that the term “Approach” is used to denote the portion of the Hover MTE starting from a stabilized hover through the 45-deg horizontal translation to the initiation of the deceleration (“Decel”).

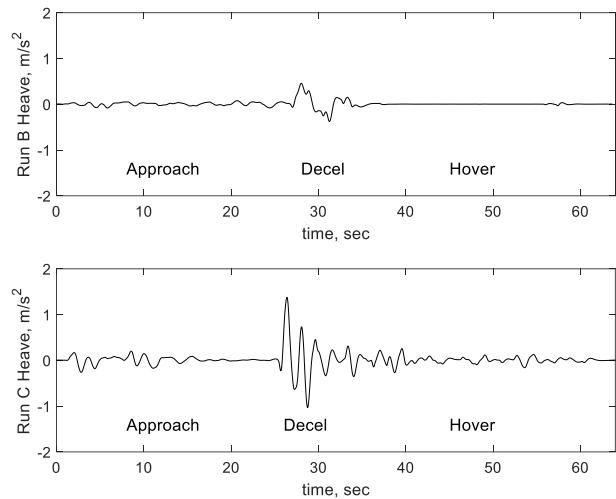


Figure 7. Time-History Comparison of the Minimum (Run B) and Maximum (Run C) Study Factor Levels.

Simulator Implementation

During the development of the study, pre-study participants reported that experiencing the VMS replay runs individually, with simulation resets between them, felt unnatural. To present a flight-like experience to the study passengers, the recordings of the pilot-flown VMS Hover MTE runs were stitched together into a single flight path (FP) using an autopilot to perform a go-around maneuver between each run. The resulting flight path was geographically re-located in the virtual environment to downtown San Francisco such that the deceleration and hover portions of the MTE were over the virtual vertiport located above the parking garage at the intersection of 5th Street and Mission Street. The stitched flight path is shown in Figure 8. The start of the approach and the final hover target were kept the same for each run to present the passengers with consistent visual cues.

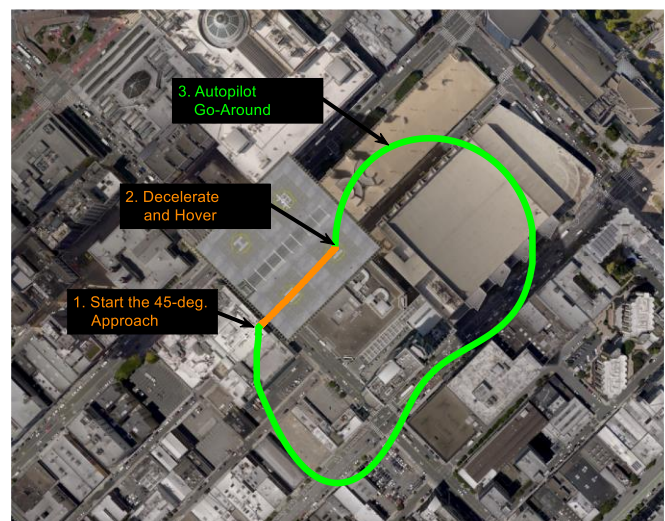


Figure 8. Stitched Flight Path: Orange: Hover MTE Course; Green: Go-Around.

A total of six stitched flight paths were created with different orderings of the VMS replay runs, as listed in Table 4. Runs B, C, and D represent the minimum, maximum, and mid-value levels of the primary study factor, respectively, and were ordered differently in each of the six FPs to allow for randomization of the order in which they are presented to the passengers. Run A, also a mid-level value of the primary study factor, was included as both the first and last run of each flight path for repeated measurements of passenger acclimation to the physical and visual motion cues. Each stitched flight path was 15 min in duration.

Table 4. Stitched Flight Paths.

FP	1 st Run	2 nd Run	3 rd Run	4 th Run	5 th Run
1	A	B	C	D	A
2	A	B	D	C	A
3	A	C	B	D	A
4	A	C	D	B	A
5	A	D	B	C	A
6	A	D	C	B	A

Each flight path was translated to a time series of hexapod pose commands using an offline classical linear washout motion cueing algorithm (Ref. 14). The motion cueing algorithm scaled and filtered the translational accelerations and yaw rate from the aircraft model to keep the dynamic platform motion within the capabilities of the hexapod actuators. Angular motion in the pitch and roll axes did not require scaling or filtering. Filtering of the heave acceleration was done using the second-order washout filter shown in Equation 1.

$$\frac{a_z^{p'}}{a_z^m} = \frac{0.6s^2}{s^2 + 2(1.0)(0.2)s + (0.2)^2} \quad (\text{Eq. 1})$$

The numerator scale factor of 0.6 was chosen to fall within the high-fidelity criteria for zero phase error given by Schroeder (Ref. 16). Phase error was minimized by time-synchronizing the visual and physical motion cues of the pre-recorded flight paths. The median time delay between physical and visual motion cues in the RQL was measured to be between 5 and 12 ms at least 95 percent of the time. The washout filter frequency and damping were selected to retain as much frequency content as possible within the physical limitations of the hexapod.

A third-order washout filter, shown in Equation 2, was applied to keep the RQL platform centered to maximize the available range of motion. The filter constants in Equation 2 were selected to keep platform centering motion effective but still imperceptible to the passenger.

$$\frac{a_z^p}{a_z^{p'}} = \frac{s^2}{s^2 + 2(1.0)(0.25)s + (0.2)^2} \cdot \frac{s}{s + 0.1} \quad (\text{Eq. 2})$$

The effect of the motion cueing algorithm on heave response at the pilot station is shown in Figure 9 for the minimum (Run B) and maximum (Run C) primary study factor levels. The same scaling and filter constants were applied to all the

stitched flight paths to allow for a consistent comparison of passenger responses. For comparison, the VMS cabin heave acceleration is also shown in Figure 9.

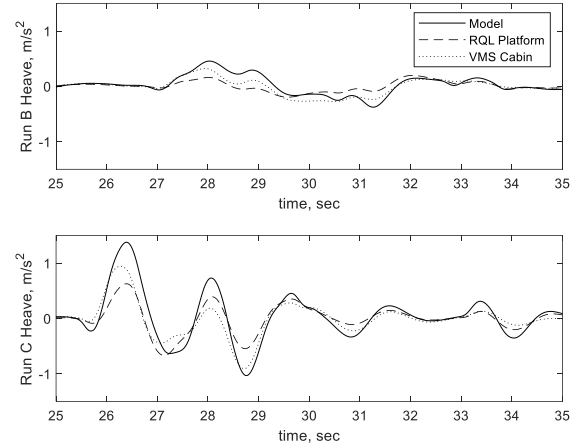


Figure 9. Comparison of Heave Acceleration Inputs and Outputs of the Motion Cueing Algorithm.

The passenger screen in the virtual cockpit was used to provide cues to the passenger. A three-second countdown preceded the start of the MTE, followed by successive prompts for the current MTE phase (“Approach”, “Decel”, and “Hover”). During the go-around, information was displayed on the screen to assist the passengers in providing ride quality ratings, discussed in further details below.

Study Size

The study was set up as a one-factor, binary outcome, within-subjects repeated-measures design in which each participant was exposed to every level of the primary study factor. Study population size was determined using statistical power tables for sign tests (Ref. 17). An expected medium effect size of 0.25 for a binomial (two-level) rating of the minimum and maximum study levels was assumed based on preliminary observations. Using a sample size table for a statistical significance of $\alpha = 0.05$, and a desired statistical power of 0.8, the minimum study population size was determined to be $n = 23$ participants.

STUDY PROTOCOL

The J³ERQ Study protocol was approved by the NASA Institutional Review Board. All members of the study team completed Collaborative Institutional Training Initiative (CITI) Human Subject Protection Training prior to interacting with the study participants.

Study Participant Criteria and Recruitment

Study participants were recruited from the NASA AFRC workforce by way of Center-wide email solicitation. The first twenty-three responses received were selected for the study, with an additional seven placed on a backup list. Prior to the start of the study, five of the initial group of participants

voluntarily withdrew and were replaced from the backup list. Participants were required to meet the following criteria:

- Be at least 18 years of age.
- Be a NASA civil servant or contract employee.
- Be unaffiliated with the RVLTL Project.
- Be able to climb a short set of steps and get into and out of a chair with minimal assistance.
- Be at least 4 ft 11 in tall and weigh between 80 and 300 lb (to meet simulator limits).
- Have normal or corrected-to-normal vision.

Once selected, all participants were screened by the AFRC Medical and Health Unit. Each participant was assigned a randomly generated Unique Study Identifier (USID) number to protect their privacy. All data collected from the participants by the study team during the study were de-identified using the USIDs, or in the case of demographics information, anonymized.

Other than their normal salary, volunteers did not receive additional compensation to participate in the study. The study was conducted during normal business hours and study activities were scheduled around the participant's other primary work duties.

Study Participant Preparation

Each participant was required to attend an informational briefing and provide informed consent. Following informed consent, participants were given two questionnaires to complete. The first questionnaire asked for demographic information, was strictly voluntary, and was submitted anonymously. The second questionnaire asked about non-sensitive background information and the participant's attitude toward flying.

Participants were brought to the laboratory for a safety briefing followed by a familiarization ride in the RQL. The familiarization ride consisted of a 4-min flight through virtual downtown San Francisco. Because some participants had never used VR or ridden in a motion simulator before, the familiarization process ensured that all participants started from as similar a baseline as was practical.

Data Collection

Participants were randomly assigned one of the six flight paths listed in Table 4. With a study population of 23, each flight path was assigned to four participants except flight path number four, which was assigned to three participants. Participants were told they would experience a series of five approaches to the vertiport, but they were not told what the study factors were, how many distinct levels of the study factors were included, or the order in which the study factors would be presented.

Data collection for each participant was scheduled on a different day from their familiarization experience to allow them time to recover and to consider whether they wanted to continue in the study. No participants withdrew from the study between familiarization and data collection. To ensure privacy and impartial evaluations, participants completed the data collection one at a time, with two members of the study team being the only other individuals present in the RQL. For consistency, most of the interaction with the participants was handled by the study Principal Investigator (PI) while the co-investigator operated the simulator.

Prior to entry into the RQL, participants were asked to complete a baseline Simulator Sickness Questionnaire (SSQ), which can be found in Ref. 18. The SSQ was administered again after the participant exited the simulator to help identify any potential physical aftereffects of the experience. The SSQ was not part of the data collection for the study.

Participants were instructed by the PI to evaluate the experience as if they were in a real aircraft, not in a simulation. To avoid the potential for undue influence or coercion, participants were also given the following instruction:

“The success of this study relies on your sincere and honest feedback about the simulated experience; it does not rely on obtaining results that fall within any specific range. You should not feel pressured or obligated to participate, or to provide responses that do not reflect your genuine assessment.”

The five MTE replays in the stitched flight path were referred to as “run one,” “run two,” and so on by the PI to the passenger. During the go-around portions of the flight, participants were asked to separately assess the approach, deceleration, and hover phases of the most recently completed run. To assist the passenger, a five-point rating scale, listed in Table 5, for each phase was displayed on the virtual screen for 20 s. The PI also read the scales to the passenger over the audio headset and asked for their ratings, which were recorded by the PI with pen and paper. In addition to the RQ ratings, passengers were asked to rate each phase of the MTE as “Comfortable” or “Not Comfortable”.

Table 5. J³ERQ Study Passenger Ride Quality Rating Scales.

RQ Rating	Approach	Decel	Hover
1	Smooth	Gentle	Smooth
2	Mostly Smooth	Gradual	Mostly Smooth
3	Bumpy	Sudden	Bumpy
4	Rough	Abrupt	Rough
5	Very Rough	Startling	Very Rough

Upon exiting the simulator, participants were asked to complete a debrief questionnaire about their experience and their level of doubt regarding a real UAM flight if it were to have the same types of motion as described in the RQ rating scales. They were also instructed not to discuss their experience or ratings with anyone else until the study was complete.

STUDY RESULTS

Ride quality ratings and passenger comfort ratings were collected from twenty-three participants for the four levels of deceleration heave motion shown in Figure 6, using the six flight paths described in Table 4. Although ratings were collected for all three phases of the MTE, only the deceleration results are presented here. Passenger feedback from the approach and hover phases from this study is inconclusive but will help to guide future studies.

Ride Quality and Comfort Ratings

Each flight path listed in Table 4 includes Run A as both the first and the last run in the replay sequence. Beginning each flight path with the same run allowed a consistent introduction to the experience for the passengers and an opportunity for the participants to practice providing ratings and establish their personal comfort criteria. Ending each flight path with the same run as at the beginning allowed assessment of whether there was a measurable acclimation effect over the course of the 15-minute experience by comparing the passenger ratings from the first and the last runs. The passenger RQ ratings and comfort responses for the deceleration phase of Run A (first and last) are shown in Figure 10.

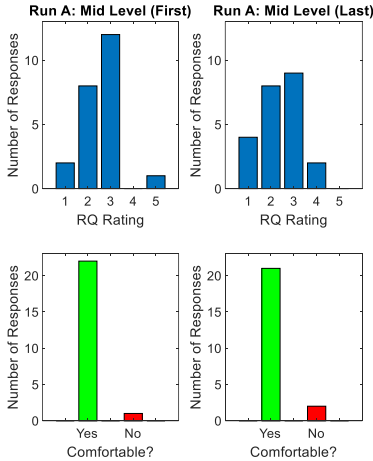


Figure 10. Passenger Ratings for Run A as the First and the Last Run in the Flight Path, Decel. Phase ($n = 23$).

Runs B, C, and D were presented to the participants in a randomly assigned order after the first Run A. Passenger RQ ratings and comfort responses for the deceleration phase of Runs B, C, and D are shown in Figure 11.

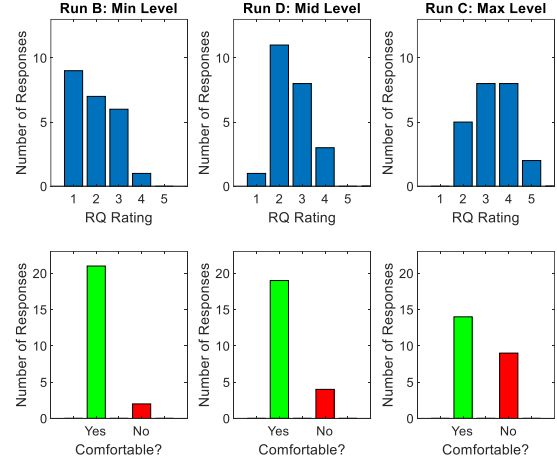


Figure 11. Passenger Ratings for Min (Run B), Mid (Run D), and Max (Run C) Levels of the Primary Study Factor During the Decel. Phase ($n = 23$).

Passenger Ratings vs. the Primary Study Factor

Estimates of the median RQ rating at each level of the primary study factor are plotted in Figure 12 along with the percentage of passengers who rated each level as “Not Comfortable”. Median RQ ratings and 95-percent confidence bounds were estimated for each level of the primary study factor using the Hodges-Lehmann and Tukey nonparametric methods, respectively (Ref. 19).

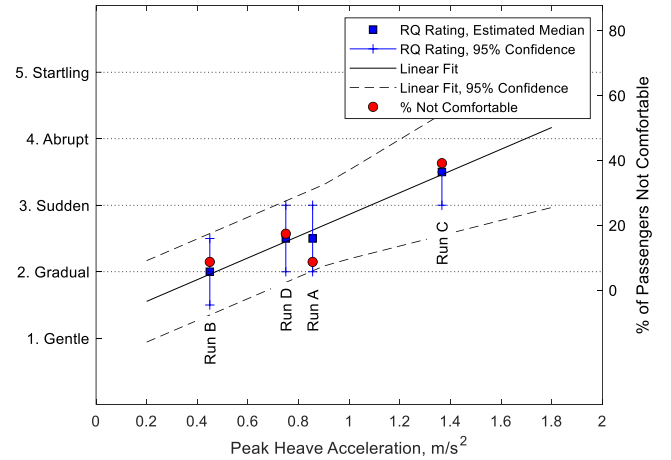


Figure 12. Passenger Ratings vs. Peak Heave Acceleration.

The linear regression fit ($R^2 = 0.98, p = 0.01$) of the median estimates of the passengers' RQ rating (C_{RQ}) to the peak heave acceleration ($\|a_z^m\|_\infty$) in m/s² during deceleration is given by Equation 3. The linear fit ($R^2 = 0.79, p = 0.12$) between the percentage of passengers not comfortable (P_{DISC}) and peak heave acceleration is given by Equation 4. Note that the test of the P_{DISC} correlation coefficient R against zero does not meet the desired level of statistical significance: $p > \alpha_{0.05}$.

$$C_{RQ} = 1.23 + 1.63\|a_z^m\|_\infty, \quad 1 \leq C_{RQ} \leq 5 \quad (\text{Eq. 3})$$

$$P_{DISC} = -10.2 + 33.5\|a_z^m\|_\infty, \quad 0 \leq P_{DISC} \leq 100\% \quad (\text{Eq. 4})$$

The right-hand axis of Figure 12 was scaled and shifted such that the linear fits of Equation 3 and Equation 4 are coincident, aligning the discomfort percentages as closely as possible to the median RQ ratings. The relationship for scaling between RQ rating and passenger discomfort axes in Figure 12 is obtained by eliminating $\|a_z^m\|_\infty$ from Equations 3 and 4 and is given in Equation 5.

$$P_{DISC} = -35.3 + 20.5C_{RQ}, \quad 0 \leq P_{DISC} \leq 100\% \quad (\text{Eq. 5})$$

Passenger Ratings vs. the Secondary Study Factor

Estimates of the median RQ rating at each level of the secondary study factor are plotted in Figure 13 along with the percentage of passengers who rated each level as “Not Comfortable”. Median RQ ratings and 95-percent confidence bounds are also shown in Figure 13.

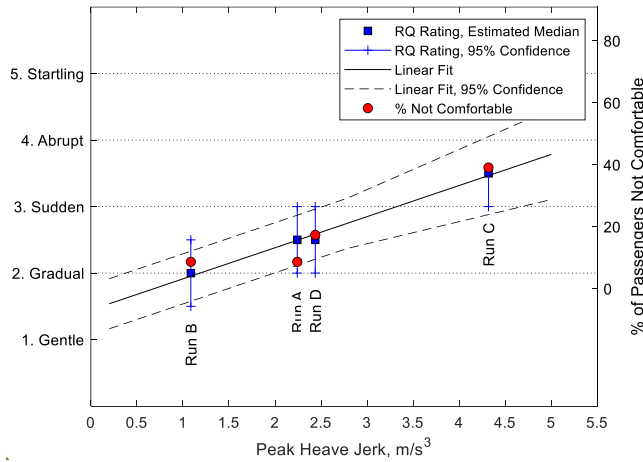


Figure 13. Passenger Ratings vs. Peak Heave Jerk.

The linear regression fit ($R^2 = 0.99, p = 0.008$) of the median estimates of the passengers’ RQ rating (C_{RQ}) to the peak heave jerk ($\|a_z^m\|_\infty$) in m/s^3 during deceleration is given by Equation 6. The linear fit ($R^2 = 0.88, p = 0.07$) between the percentage of passengers not comfortable (P_{DISC}) and peak heave jerk is given by Equation 7. Note again that the test of the P_{DISC} correlation coefficient R against zero does not meet the desired level of statistical significance: $p > \alpha_{0.05}$.

$$C_{RQ} = 1.45 + 0.47\|a_z^m\|_\infty, \quad 1 \leq C_{RQ} \leq 5 \quad (\text{Eq. 6})$$

$$P_{DISC} = -6.84 + 10.0\|a_z^m\|_\infty, \quad 0 \leq P_{DISC} \leq 100\% \quad (\text{Eq. 7})$$

The right-hand axis of Figure 13 was scaled and shifted in the same manner as that of Figure 12. The relationship for scaling between RQ rating and passenger discomfort axes in Figure 13 is given in Equation 8.

$$P_{DISC} = -37.9 + 21.5C_{RQ}, \quad 0 \leq P_{DISC} \leq 100\% \quad (\text{Eq. 8})$$

Passenger Comments

Passengers were asked to complete a debrief questionnaire upon exiting the simulator. The questionnaire included open-ended questions about the experience. Table 6 lists sample responses to these questions from participants who rated one or more aspects of the flight as “Not Comfortable.”

Table 6. Sample Relevant Debrief Questionnaire Responses.

Debrief Question	Sample Responses from the “Not Comfortable” Group
<i>Please elaborate on any feelings of discomfort you felt during the experience.</i>	“Decel surprise angle.” “The accelerations during decel were higher/different than I might have expected.” “The sudden direction change on the deceleration was extreme compared to what I expected.”
<i>What would have made you feel less uncomfortable?</i>	“Gentle approach initiation and deceleration.” “Slower accelerations... more gradual onset.” “Slower or more gradual deceleration or direction change and angle change.” “Having a smoother transition between approach and hover would help.”

Passenger Acceptance

To better understand the types of motion that passengers might be willing to accept, participants were asked in the debrief questionnaire to relate the motion descriptions in the RQ rating scale to their level of doubt about taking a real UAM flight. This part of the questionnaire is modeled on the work of Richards and Jacobson (Ref. 20). Tabulated responses for the “Decel” RQ scale are given in Table 7.

The percentage of passenger acceptance responses from Table 7 that fall into the “No Doubts” categories are plotted in Figure 14 along with the results published by Richards and Jacobson (Ref. 20). It should be noted that the five-point RQ scale in Ref. 20 uses different adjectival descriptors from the “Decel” column of Table 5, and that the data in Ref. 20 were collected from passengers who had flown on commuter airliners, rather than on UAM aircraft.

Table 7. Passenger Acceptance Questionnaire Results for Deceleration Motion.

For an air taxi with the indicated level of motion, I would:		Gentle	Gradual	Sudden	Abrupt	Startling
No Doubts	Be eager to take a real flight	17	15	5	0	0
	Take a real flight without any doubts	6	8	11	9	5
Doubts	Take a real flight with some doubts	0	0	7	11	9
	Prefer not to take a real flight	0	0	0	3	6
	Definitely not take a real flight	0	0	0	0	3

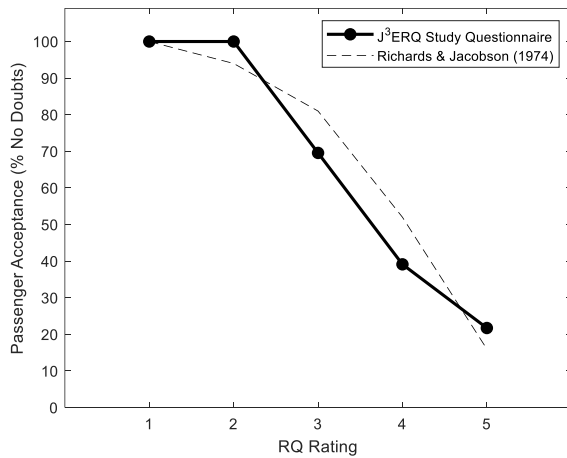


Figure 14. Passenger Acceptance vs. RQ Rating.

DISCUSSION

Distinguishable Levels of Motion

The first objective of the J³ERQ Study was to identify the levels of sudden motion that may be distinguishable to the UAM passenger. The null hypothesis that the RQ ratings between the four runs are *not* distinguishable can be evaluated using the Wilcoxon and Wilcoxon Rank Test for Multiple Comparisons of Correlated Samples (Ref. 21). Using this test, Run C was found to be distinguishable from Runs A and B ($p < 0.01$) and from Run D ($p < 0.05$). Run B was not distinguishable from Run D ($p > 0.05$). Run A could not be distinguished ($p > 0.10$) from either Run B or Run D in terms of RQ rating.

The null hypothesis that passenger comfort ratings are not distinguishable between a pair of runs can be evaluated using the Binomial Test (Ref. 22). Using this test, Run C was found to be distinguishable ($p < 0.02$) from the other runs. The

difference in comfort rating between each pairing of the lower levels could not be sufficiently distinguished ($p > 0.10$).

These results indicate that thresholds for changes in passenger comfort level may be approximately 0.5 m/s^2 for jolting (Run C versus Run A) and 1.9 m/s^3 for jerking (Run C versus Run D).

Potential Influencing Factors

A total of nine study participants, referred to hereafter as the discomfort group, provided a “Not Comfortable” rating for one or more of the study factor levels. It should be noted that participants reporting discomfort for Runs A, B, and D, are all members of the discomfort group for Run C. Table 8 lists possible influencing factors from the participants’ background questionnaires and a comparison of the responses from the discomfort group versus those of the overall study group. See Appendix A for a more detailed tabulation of the participant responses to these questions.

Table 8. Comparison of Potential Influencing Factors: Discomfort Group vs. Study Group.

	Discomfort Group, %	Study Group, %
General Flight Experience		
Rarely Fly	44	17
Positive Attitude Toward Flying	67	74
Does Not Find Air Travel Comfortable	22	17
Listed Comfort as an Important UAM Factor	11	26
Aircraft Knowledge: None to Average	33	35
Pilot Experience	22	22
Helicopter Passenger Experience	56	57
Simulation Experience		
VR Experience: None to Little	78	83
Motion Sim Experience: None to Little	89	83
Physiological Factors		
Somewhat or Very Prone to Motion Sickness	22	26
Somewhat or Very Prone to Vertigo	0	4
Highly Sensitive to Up-and-Down Motion	33	39
Highly Sensitive to Side-to-Side Motion	22	39

Members of the discomfort group fly less often than the average for the study group. In fact, all four participants who said they rarely fly (once or fewer times per year) are in the discomfort group. Of the four participants who reported flying frequently (several times per month), only one fell into the discomfort group. Interestingly, members of the discomfort group were less likely to mention comfort as factor or concern with the UAM system, did not report finding air travel less comfortable at a notably higher rate, and had about the same rate of positive attitudes toward flight. These results may indicate that passengers who do not fly often may find sudden motion uncomfortable at first due to its unfamiliarity but may acclimate if they become more frequent air travelers.

A lack of familiarity with virtual reality and motion-base simulators appears to have had little influence on the results of the study, as did propensity for motion sickness and vertigo. Members of the discomfort group had about the same sensitivity to up-and-down motion as did the general study group but were less likely to be sensitive to side-to-side motion - perhaps evidence that the discomfort ratings were given because of heave motion and not motion in the other axes.

Passenger Acceptance

To provide guidance to the UAM industry, it would be useful to relate levels of sudden heave motion to the willingness of passengers to fly on aircraft having those motion characteristics. Using the relationship between peak heave acceleration and RQ rating given by Equation 3, Figure 15 plots the passenger acceptance results in Table 7 against the primary study factor levels. Figure 16 plots the passenger acceptance results in Table 7 against the secondary study factor levels, using Equation 6 to relate RQ rating to level of jerk.

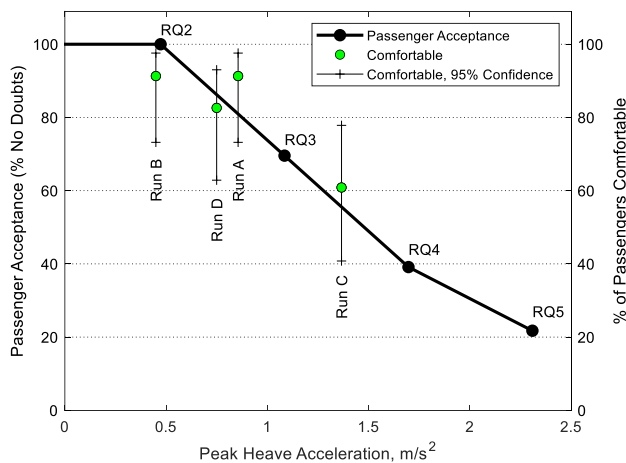


Figure 15. Passenger Acceptance and Comfort vs. the Primary Study Factor: Peak Heave Acceleration.

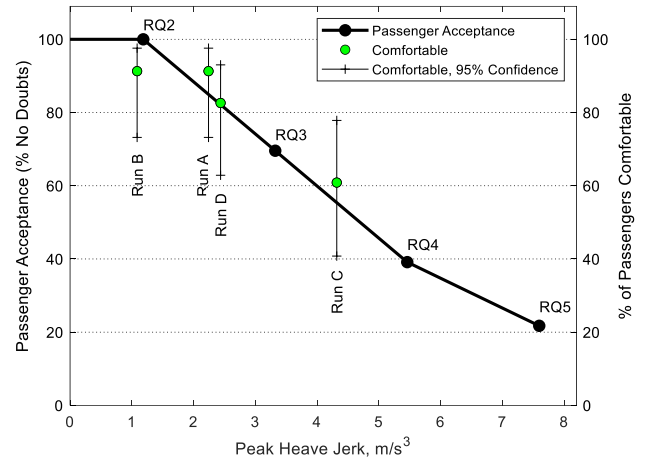


Figure 16. Passenger Acceptance and Comfort vs. the Secondary Study Factor: Peak Heave Jerk.

Under the assumption that passenger acceptance corresponds to passenger comfort, the percentages of passengers who gave “Comfortable” ratings for the four runs are also plotted in Figures 15 and 16. The relationship between passenger acceptance and comfort for the primary study factor based on the study results has an RMS error of 7.5 percent, and for the secondary study factor has an RMS error of 6.3 percent. The target goal for passenger acceptance and comfort level is a business decision for UAM operators and is not an objective of this study.

Participant Acclimation During the Experience

On the background questionnaire, 19 of the 23 participants reported having experienced both virtual reality and motion-base simulators fewer than five times in the past five years. The large proportion of participants for whom the RQL VR simulator was an unfamiliar experience prompted an assessment of whether they were acclimating to the environment during the study.

Recall that each flight path experienced by the test subjects started and ended with the same MTE replay: Run A. By comparing the results between the first and last runs, shown in Figure 10, a determination can be made whether the passengers’ evaluations were influenced by an acclimation effect.

The Wilcoxon Signed Rank Test failed to reject the null hypothesis ($p = 0.19$) that the RQ ratings for the first and last runs are statistically different from one another. The nonparametric Hodges-Lehmann method estimated the median RQ rating to be 2.5 for both the first and last run of the sequence. Finally, the Binomial Test failed to reject the null hypothesis ($p = 0.26$) that the occurrence of “Not Comfortable” ratings for the two runs are statistically different from one another. The statistical analysis failed to detect a measurable acclimation effect during the test.

Potential Biases in the Study Population

All volunteers in this study were NASA civil servant or contract employees at the time of their participation. The volunteers were not drawn from the general population, so the potential exists for biases that may affect the results of the study. Demographic information about the study group was collected with a questionnaire that asked about potentially sensitive aspects of the participants' identity. The questionnaire was voluntary and submitted anonymously. Twenty-one of the twenty-three study participants submitted responses to this questionnaire which are summarized in Appendix B. Selected categories are discussed below.

Seventy-six percent of the J³ERQ study participants were male, and 24 percent were female, compared to 49.5 percent and 50.5 percent, respectively, for the U.S. population (Ref. 23). Figure 17 shows the study population age distribution. The requirement that volunteers be over the age of 18 and employed at NASA resulted in under-representation below 25 and over 65 years of age. The percentage of the study population between the ages of 35 and 64 was much higher than that of the general U.S. population.

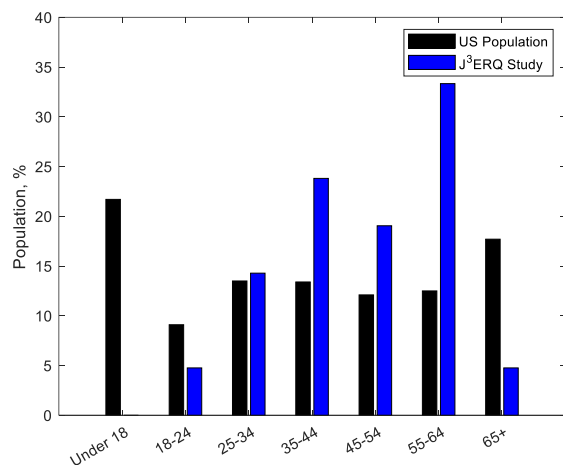


Figure 17. Study Age Distribution.

The race and ethnicity distribution of the study population is shown in Figure 18. The study had a larger population of Hispanic and Latino volunteers than the general U.S. population (Ref. 23). There were no participants in the study who identified as Black or African American. Participants tended to be more highly educated than the U.S. public, as shown in Figure 19.

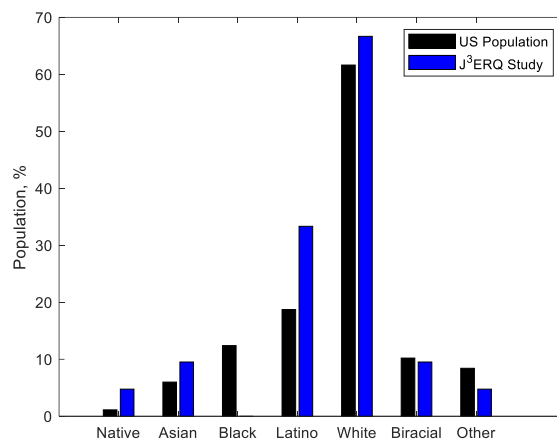


Figure 18. Study Race and Ethnicity Distribution.

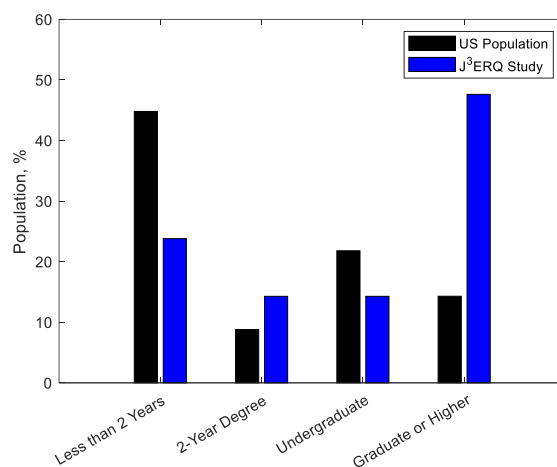


Figure 19. Study Education Level Distribution.

The information presented above is included to inform readers of potential biases in the study population, and to guide future researchers as to areas that may warrant additional scrutiny. There is not enough information to determine, nor was the intent to determine, whether or how the sex, age, race and ethnicity, and education level distribution of the study group may have affected the results of this study.

It was noted earlier that study participants who fly one or fewer times per year were significantly more likely to rate portions of the study as “Not Comfortable” than those who fly more often. These infrequent fliers are typical of 51 percent of the U.S. adult population (Ref. 24), compared to only 17 percent within the study, perhaps indicating that a higher discomfort rate could be expected for members of the public than what was reported in this study. The percentage of individuals with a positive attitude toward flying is about the same between the public (71 percent, Ref. 24) and the study group (74 percent).

The recruitment e-mail did not describe the type of motion involved in the study but did state that participants would be passengers in a virtual reality motion simulator. It is possible that individuals who are prone to motion sickness or vertigo chose not to volunteer. As discussed earlier, the participant group who evaluated one or more aspects of the experience as “Not Comfortable” were no more likely to self-report as somewhat or very prone to motion sickness or vertigo than the overall study group. There is no evidence that self-selection for these factors biased the results of the study.

Adverse Results

A Motion Sickness Dose Value of 0.78 was calculated as described in Ref. 25 for the 15-minute simulations used in the study, indicating that 0.26 percent, or about 1 in 400 individuals, would be expected to become sick enough to vomit from the experience. Of the study group, 26 percent self-reported that they are somewhat prone to motion sickness. Participants were briefed that they could stop the simulation at any time if they were not feeling well or did not want to continue for any reason. All 23 of the volunteers who participated in the safety briefing and familiarization ride also completed the data collection portion of the study. Although results of the SSQ were not shared with the PI, none of the participants voluntarily reported symptoms. There is no evidence that simulator or motion sickness affected the results of the study, although it should be noted that sensitive individuals might have declined to enroll in the study.

CONCLUSIONS

Twenty-three human subject volunteers participated in a study of sudden heave motion on passenger comfort and ride quality in a virtual reality simulator with a motion base. Four levels of the study factors were presented to the participants as a series of five approaches to deceleration and hover over an elevated vertiport. The first and last runs were identical replays of a medium level of the study factors. The remaining three runs, representing the minimum, medium, and maximum levels of the study factors, were presented in a randomized order.

Participants provided evaluations after each approach using a five-point ride quality rating scale, as well as a binary “Comfortable” or “Not Comfortable” rating. Demographic and background information was collected from the participants, and after their simulator entry participants were given a debrief questionnaire and asked to estimate their level of doubt about flying in a real aircraft for each level of motion on the RQ rating scale. Conclusions from this study are summarized as follows.

1. Participants were able to distinguish the maximum level of motion from the other levels in the study using the RQ rating scale. The minimum and two medium levels were not distinguishable from one another.

2. Participants’ comfort level was significantly lower for the maximum motion level than for the other levels. The differences in comfort level between the minimum and medium levels were not statistically significant.
3. Relationships were established between sudden heave motion characteristics, doubts about flying in a real aircraft, and passenger discomfort.
4. Flying once or fewer times per year was identified as a potential contributing background factor of the group who rated one or more levels of the study factors to be “Not Comfortable”.

Recommendations

The authors propose the following recommendations.

1. The results of this study should be replicated, preferably through in-flight passenger studies using representative aircraft. Replication of results is important to increase confidence in the conclusions of the study. An evaluation of the results in representative flight environments will enhance the generalization of these results to UAM operations.
2. Follow-on studies should be carried out to extend to higher levels of motion, e.g., peak heave acceleration between 1.5 and 2.5 m/s². The current study did not yield passenger discomfort rates above 40 percent, leaving more extreme conditions in the realm of extrapolation.
3. Follow-on studies should be carried out to differentiate passenger comfort response to the specific aspects of motion contained within this study. For example, it is unclear from the results of this study whether the participants were responding primarily to jolting or to jerking.
4. A longitudinal study should be undertaken to identify whether repeated, frequent flight-like experiences such as the one on this study reduce passenger discomfort. Such a study would shed more light on the frequent flier contributing factor identified in this study.

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APPENDIX A – PARTICIPANT BACKGROUND QUESTIONNAIRE RESPONSES

A questionnaire was given to study volunteers before their simulator entry to collect background information about their attitudes and experience related to flight and other factors that might influence their responses in the study. A summary of the Background Questionnaire responses is listed in Table A.

Table A. Summary of J³ERQ Study Non-Sensitive Demographics Responses.

Question	Choices	Responses
Handedness	Left	3
	Right	20
	No Preference	0
Prone to Motion Sickness	Not at all	17
	Somewhat	6
	Very	0
Prone to Vertigo	Not at all	22
	Somewhat	0
	Very	1
Pilot's License	Yes	5
	No	18
Times Flown in a Helicopter	0	10
	1-3	9
	4 or more	4
General Aircraft Knowledge	Unfamiliar	2
	Average	6
	Above Average	12
	Expert	3
Household has a VR System?	Yes	6
	No	17
VR Usage Over the Past 5 Years	0	8
	1-4	11
	5-10	0
	10+ but infrequent	2
	Frequent/Regular	2
Motion Simulator Experiences Over the Past 5 Years	0	8
	1-4	11
	5-10	3
	10+ but infrequent	0
	Frequent/Regular	1
How do you feel about flying?	Negative	1
	Neutral	5
	Positive	17
How often do you fly?	Rarely	4
	Several times per year	15
	Several times per month	4
Air Travel is Comfortable	Strongly Disagree	1
	Disagree	1
	Uncertain	2
	Agree	15
	Strongly Agree	4
Easy to Relax While Flying	Strongly Disagree	0
	Disagree	1
	Uncertain	2
	Agree	13
	Strongly Agree	7
Significance of Up and Down Motion on Comfort	Unimportant	3
	Very Little Importance	3
	Somewhat Important	8
	Very Important	6
	Greatest Importance	3

Significance of Side-to-Side Motion on Comfort	Unimportant	3
	Very Little Importance	1
	Somewhat Important	10
	Very Important	4
	Greatest Importance	5
Mentioned Comfort as a UAM Factor or Concern	Yes	6
	No	17

APPENDIX B – STUDY DEMOGRAPHICS

A questionnaire was given to study volunteers before their simulator entry to collect information on the demographic makeup of the study group. This questionnaire was anonymous and voluntary; not all participants chose to submit responses. Responses were submitted to a member of the study team other than the Principal Investigator (PI). The study PI did not receive individual submissions, only the aggregated responses shown in Table B. Some questions that were asked as part of the demographics questionnaire are not being reported in order to comply with a recent Presidential Executive Order, (“Defending Women From Gender Ideology Extremism And Restoring Biological Truth To The Federal Government,” dated January 20, 2025).

Table B. Summary of Study Participant Demographics.

Question	Choices	Responses
Age	18-24	1
	25-34	3
	35-44	5
	45-54	4
	55-64	7
	65+	1
Sex	Female	5
	Male	16
	I prefer not to respond	0
Race / Ethnicity (Select all that apply)	Native American or Alaskan	1
	Native	2
	Asian	0
	Black or African American	7
	Hispanic or Latino	1
	Native Hawaiian or Pacific Islander	14
	White or Caucasian	2
	Multiracial or Biracial	0
	Not Listed	0
	I prefer not to respond	0
Level of Education	Less than a 2-year degree	5
	2-year degree	3
	Undergraduate degree	3
	Graduate degree or above	10

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