

Measuring the Effect of Electric Vertical Takeoff and Landing Aircraft Configurations on Pilot Learning and Performance

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Abstract

Most emerging electric vertical takeoff and landing (eVTOL) aircraft feature distributed electric propulsion systems with automation features that simplify operations for future pilots. Increasing automation levels should reduce pilot workload, decrease training time, and improve performance consistency. Air Education and Training Command Detachment 62 (AETC/Det 62) sought to test this theory by conducting a study that involved 80+ participants, two simulated eVTOL platforms, and multimodal assessments of flight performance. This report details the results of six separate sub-studies including 1. Measuring the innate capacity of the subjects in the study using a battery of psychometric tests. 2. Measuring automation impacts on human performance using expert ratings of rated pilots while performing hovering, takeoff, on-the-wing enroute navigation, and approach and landing maneuvers in either highly-automated or semi-automated eVTOL platforms. 3. Comparing the learning trajectories of ab initio participants with those of rated pilots in the two eVTOL simulators. 4. Comparing the performance of 10 rated rotary-wing pilots to the average performance of fixed-wing pilots. 5. Assessing performance improvements in airspeed and altitude control by comparing system-based data from each of the simulators. 6. Aggregating participant responses to questions related to flying the aircraft using thematic analysis. Overall, the results of these six sub-studies revealed that increased levels of automation improved flight performance and learning outcomes. Competent levels of performance were seen in both platforms and in both groups of participants after two hours of experience flying the simulated profile. This study provides empirical data measuring human and machine performance in eVTOL simulators. This study may be used to inform aviation policy, develop training programs, and influence design decisions in the aircraft.

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Introduction

The upcoming electric vertical takeoff and landing (eVTOL) aircraft market is predicted to add several hundred thousand aircraft to the national airspace. In the next 10 years, these vehicles will use control systems and propulsion schemes that resemble nothing that was flown since the beginning of powered flight. Modern technology will take on many traditional piloting skills with high degree of reliability. These aircraft will need a new classification of operator that embodies the ethos of airmanship and safety in a crowded environment, and the skills to operate a highly automated aircraft. However, pilots need to merge into a century-old ecosystem of aircraft, training, controls, and certification.

New eVTOL aircraft using highly automated flight controls and integrated navigation systems require a new set of skills to ensure a safe and competent operation. Currently, pilot certification requires operators to train in aircraft with legacy propulsion and control systems.

Background

Over 600 eVTOL models are in development around the world (Vertical Flight Society, 2022). Pundits speculate that production of these vehicles will skyrocket in the near future. As battery technology improves, the value proposition for clean, quiet, electric aircraft will continue to drive development. Over 350 manufacturers (Vertical Flight Society, 2022) are all looking for a way to carve out a niche in this new market. Many developers are banking on fully autonomous vehicles to maximize profits. But the reality is that federal regulatory agencies and the flying public are not ready to step into pilotless aircraft. This means the industry will need pilots to get to get off the ground, both literally and figuratively. Training pilots to operate a new class of aircraft will be an essential step in developing this industry to a sustainable level. Early iterations of eVTOLs are likely to employ high levels of automation to simplify flight operations and improve safety. In theory, these improvements would reduce the time required to develop competent pilots. However, no one has tested this theory by training a significant number of current pilots and/or ab-initio participants.

eVTOL prototypes currently in development have varying degrees of and approaches to simplified vehicle operations (SVO), such as stability, airspeed, and altitude (Donateo et al., 2022). According to the General Aviation Manufacturers Association (GAMA) (2019), “SVO is automation coupled with human factors best practices to reduce the number of trained skills and knowledge that the pilot of an aircraft must acquire to operate the system at the required level of operational safety.” Manufacturers the SVO features present in eVTOLs will make them easier to operate, with the expectation that automation will decrease pilot workload and increase safety when compared to conventional aircraft. Furthermore, GAMA (2019) expects increased automation of SVO could reduce training times (Holbrook et al., 2020). Reducing training times has a large benefit as the skills and knowledge necessary to pilot conventional aircraft in various environments and situations is expensive and resource-intensive (GAO, 2018).

Problem Statement

Ideally, operators of modern eVTOL aircraft will train to develop relevant competencies using modern training methods and equipment. Unfortunately, there is no path to Airman certification using the proposed control, propulsion, and automation systems. If we don't develop training programs that provide relevant skills and abilities in a timely manner, the U.S. will not be able to keep up with the rest of the world when these aircraft systems are fielded.

Training pilots operating eVTOL vehicles using SVO will affect how quickly they develop new skills and reach qualification standards. Pilot's training for the UAM environment, assisted by SVO features, could accomplish the required level of operational safety in a shorter timeline. The data in Table 1 shows the average training times for several skills in conventional aircraft in the Embry Riddle Aeronautical University training fleet (Duerksen & Martos, 2021).

Table 1. Average Training Times in Conventional Aircraft

Competency	Hours
Hovering Maneuvers (Rotary)	6.3
Takeoff, Landing, and Go-Around (Rotary)	6.7
Performance and Ground Reference Maneuvers (Fixed)	7.7
Navigation (Fixed)	5.6

Purpose Statement

This study measured the impact different levels of SVO had on how the subjects learned to fly simulated aircraft. It compared the learnability of various control schemas with ab-initio participants and experienced pilots. The goal of this study was to identify differences in participant performance, using modern eVTOL simulators. The data from this study will help determine how to develop mastery of flying competencies required for safe and effective aircraft operations.

Research Objectives

- RO1. Measure cognitive and psychomotor resource availability.
- RO2. Evaluate the performance of participants in simulated flight operations.
- RO3. Describe the learning trajectories of rated pilots and ab initio participants in eVTOLs
- RO4. Compare the performance of rotary-wing pilots to fixed-wing pilots in eVTOLs
- RO5. Evaluate pilot performance using simulator data outputs
- RO6. Describe participant impressions of performance and learnability.

Researchers collected the following data to support these research objective demographic information, including education level, age, gender, and aviation experience.

Pilot performance criteria including scenario execution, knowledge of pilotage skills. Exit interviews conducted by neutral parties will gather participant perceptions and narratives supporting qualitative analysis.

Theoretical Framework

The figure below shows how the control group (experienced pilots) and the experimental group (Ab Initio participants) flowed through the experiment and where measures were taken to support the research objectives. One experienced pilot and one Ab Initio participant entered the program each day. Demographic information was collected from subjects when they arrived at the training location. A battery of psychometric tests will be used to assess the subjects' performance limitations based on their cognitive resource availability (RO1). The participants flipped a coin to determine which will fly the more automated and which will fly the less automated aircraft simulator. Participants were given ground instruction in the operation of their aircraft simulator and learned how to perform required tasks. Each participant was given an identical mission scenario requiring them to takeoff, navigate and land at designated locations. Participants flew the scenario while an instructor/evaluator assessed their performance using a subjective assessment tool. Participants repeated the flight profile four times while being evaluated (RO2). Researchers performed a post hoc analysis of data collected from the simulators to determine if there were any significant differences in flight stability between runs 1 and four (RO5). After completing the flight simulator portion of the assessment, participants were given a posttest to measure their knowledge retention of the eVTOL they flew and completed a questionnaire to gather their perceptions of their performance and the effectiveness of the learning experience (RO6).

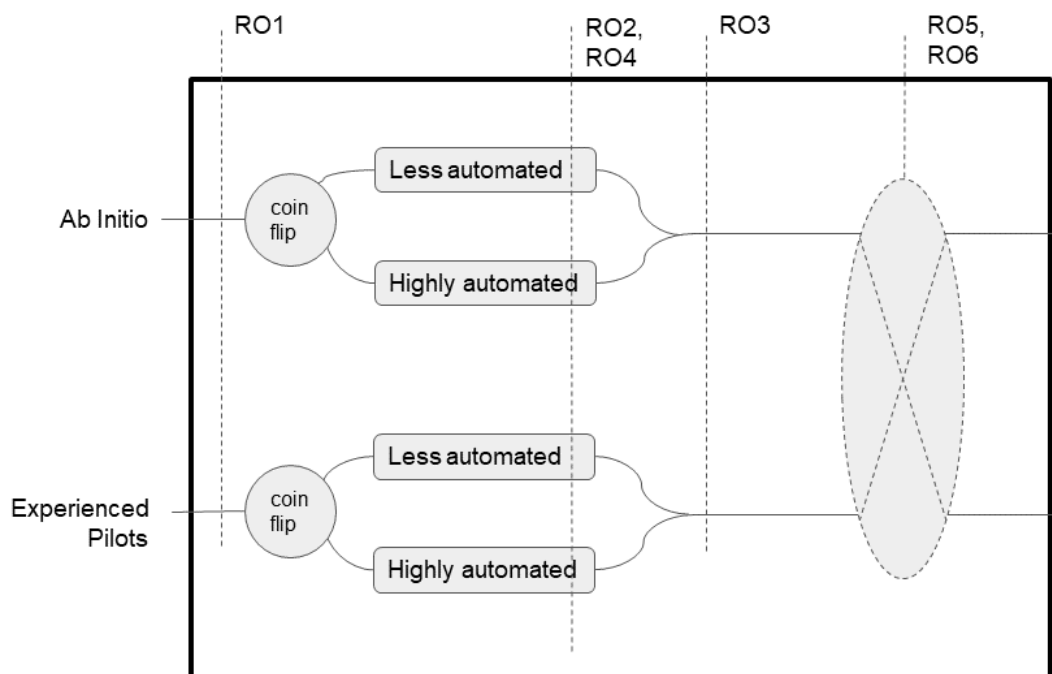


Figure 1 Theoretical Construct

Significance of the Study

The U.S. will need up to 60,000 pilots in the next 10 years to meet the demand caused by the emergence of the eVTOL market (Pelli & Riedel, n.d.). Current training to become a commercial pilot, with instrument and multi-engine ratings takes several years and costs upwards of \$25,000 (Hampton et al., 2017). This represents a total burden of between \$4 - \$6 billion (Pelli & Riedel, n.d.). This barrier to entry will severely limit the numbers of available pilots and still not match the skills and competencies needed for this advanced type of aircraft. This study shows the learning curve for various levels of SVO and provides insight on how to train the next generation of eVTOL pilots most efficiently to ensure safe operations.

Delimitations

Participants in this research will be selected from Air Force members or experienced pilots in the Joint-Base San Antonio area, Washington D.C. area, and Dayton OH area. As such, these participants may not represent the larger population of all potential eVTOL pilots. The exercise will be conducted and evaluated on a limited set of competencies that were selected to represent the larger set of eVTOL pilot competencies. Researchers limited the scenario to allow the subjects to complete four runs in a single day. This scenario did not include adverse conditions, darkness, weather, wind, or emergency procedures. This scenario did not include basic Airmanship skills such as situational awareness, crosscheck, and speaking with Air Traffic control.

Limitations

The subjects in this study were evaluated on aircraft simulators only. Actual flight training in eVTOL aircraft will not be possible until the aircraft are produced and certified for manned flight. It is important to note that this work is a first step in examining eVTOL platforms and pilot types and there are some limitations of the current work. The training requirements in the present study were limited to learning trajectories for stick and rudder skills only and did not include other vital aviation skills (e.g., ground training, emergency procedures, and communication). Any future pilot curricula will need to consider these other foundational competencies, especially in training for ab initio pilots. Furthermore, predictions for the amount of time necessary to reach proficiency were based on the learning trajectories seen within a limited number of repetitions of the flight profile. Future research will need to validate these predictions by extending the amount of training time included in the experiment. The environment in which the participants flew was a “fair weather” environment that did not incorporate any adverse weather such as wind, rain, or fog. Weather is a vital component in training as it greatly impacts aircraft handling; additionally, eVTOL pilots will face additional weather challenges such as mechanical wind turbulence. Future research should examine the impacts of adverse and mechanical wind turbulence for future pilots as it will be imperative for training. It is important to note that initial operations are expected to be conducted in fair weather and under visual flight rules. Further, the study

examined only two simulated vehicles. While these two vehicles are representative of very different levels of automation, they do not span the wide variety of eVTOL vehicle types. Future research should be conducted with a greater variety of vehicle types once the vehicles and simulators more closely represent the final aircraft designs.

Chapter Summary

This study analyzes qualitative and quantitative data captured from experienced pilots and ab-initio participants on various simulators representing various levels of automation in eVTOL configurations. All participants received identical training scenarios and ground instruction. The data researchers collected measured pilot competencies and performance parameters. Additionally, exit surveys identified common themes in participant perception of learnability and pilot readiness.

Methods

Research Design

This study follows a parallel QUANT+ Qual mixed-methods research design (Creswell & Plano Clark, 2011). Researchers analyzed quantitative data collected from aircraft simulators to measure individual participant performance against an exemplar flight profile. FAA/Air Force certified instructor pilots collected qualitative data through automated assessment tools and exit interviews. We collected and analyzed qualitative data to add richness to the participant performance data as well as to triangulate our findings.

Population and Sample

The target population was Air Force members in career fields that would potentially support mission sets for eVTOL operations. The sample consisted of Air Force members in the Joint-Base San Antonio area. Ab initio participants with no prior flying experience or training were also included in the experiment. Approximately 40 subjects were needed to fly each simulator to provide statistically significant results. Det 62 recruited a total of $n = 86$ individuals that participated in the study (see Table 2). Participants were from Joint Base San Antonio, TX, Washington, DC, and Springfield, OH. Not all of the 86 participants completed the study, see. Total Sample Demographics

Table 2. Total Sample Demographics

	Highly Automated		Semi-Automated	
	Pilot	Ab initio	Pilot	Ab initio
Age				
<i>M</i>	43.11	36.29	40.24	33.52
<i>SD</i>	13.07	7.13	8.03	7.42
Range	26-69	25-51	26-58	21-49
Gender				
Female	2	5	2	4
Male	18	19	19	17
Total	20	24	21	21

Study Samples

Aviation Experience.

This study included $n = 75$ participants to examine the differences between ab initio and rated pilots. Thirty-six were ab initio and 39 were rated pilots. Of the rated pilots, 39 had fixed-wing and four had rotary-wing experience.

Pilot performance using simulator data outputs.

The sample for the system-based analysis included 10 male volunteers (mean age = 45 years, SD = 9) from the USAF Joint Base San Antonio. All 10 participants had fixed-wing flight experience, and none of the participants with other aircraft experiences were included. Participants in the semi-automated and highly automated platforms had an average total number of 3,534 flight hours (SD = 436) and 3,772 flight hours (SD = 606), respectively.

Participant impressions of performance and learnability.

A total of $n = 65$ participants filled out the self-report data That was included in the qualitative analysis. Issues with the survey software led to a lack of data for $n = 10$ participants. A total of $n = 37$ individuals (18 ab initio and 19 rated) were in the semi-automated group, while $n = 28$ individuals (13 ab initio and 15 rated) were in the highly-automated group.

Sampling Procedures

A combination of snowball and convenience sampling will be used to recruit subjects for this study. Researchers used convenience sampling (Shadish et al., 2002) to identify ab-initio participants. Subjects were randomly assigned to simulators of various automation levels based on a coin flip.

Instrumentation

Quantitative and qualitative data was collected from several sources to support the research objectives. One or more data sources will be mapped to each research objective as shown in . Sources of data include a participant questionnaire, pre-/posttest of general aviation knowledge, aircraft simulator data collected through the Performance Evaluation Training System (PETS), subjective assessments collected through SPOTLITE, and a post-event participant survey.

Table 3 Data source and analysis

Variable	Source	Research Objective	Data Type	Analysis Method
Age	Questionnaire		Scalar	Descriptive Statistics
Airplane flight hours	Questionnaire		Scalar	Descriptive Statistics
Helicopter flight hours	Questionnaire		Scalar	Descriptive Statistics
Drone Flight hours	Questionnaire		Scalar	Descriptive Statistics
Gender	Questionnaire		Nominal	Descriptive Statistics
Education	Questionnaire		Scalar	Descriptive Statistics
Multi-limb coordination,	Two arm	RO1	Scalar	Univariate

speed	coordination test			Analysis
Multi-limb coordination, accuracy	Two arm coordination test	RO1	Scalar	Univariate Analysis
Multi-limb coordination, throughput	Two arm coordination test	RO1	Scalar	Univariate Analysis
Visual motor prediction accuracy	Vienna test system	RO1	Scalar	Univariate Analysis
Visual motor tracking accuracy	Vienna test system	RO1	Scalar	Univariate Analysis
Multi-choice reaction speed	Vienna test system	RO1	Scalar	Univariate Analysis
Math speed	ANAM	RO1	Scalar	Univariate Analysis
Math accuracy	ANAM	RO1	Scalar	Univariate Analysis
Math throughput	Synthesis	RO1	Scalar	Univariate Analysis
Spatial orientation speed	ANAM	RO1	Scalar	Univariate Analysis
Spatial orientation accuracy	ANAM	RO1	Scalar	Univariate Analysis
Spatial orientation throughput	ANAM	RO1	Scalar	Univariate Analysis
Switching speed	ANAM	RO1	Scalar	Univariate Analysis
Switching accuracy	ANAM	RO1	Scalar	Univariate Analysis
switching throughput	ANAM	RO1	Scalar	Univariate Analysis
Perceptual integration capacity (concealed words)	Psychometric test	RO1	Scalar	Univariate Analysis
Perceptual integration	Psychometric	RO1	Scalar	Univariate

capacity (snowy pictures)	test			Analysis
Maintain desired airspeed	PETS	RO4	Scalar	Visual analysis
Maintain desired altitude	PETS	RO4	Scalar	Visual analysis
Maintain desired heading	PETS	RO4	Scalar	Visual analysis
Maintain desired course	PETS	RO4	Scalar	Visual analysis
Proficiency in hover	SPOTLITE	RO2, 3, 4	Interval	Quantative Analysis
Proficiency during takeoff	SPOTLITE	RO2, 3, 4	Interval	Quantative Analysis
Proficiency during enroute navigation	SPOTLITE	RO2, 3, 4	Interval	Quantative Analysis
Proficiency during approach and landing	SPOTLITE	RO2, 3, 4	Interval	Quantative Analysis
Impressions of difficulty	Exit Survey	RO6	Qualitative	Thematic Analysis
Self-assessment of participant stress	Exit Survey	RO6	Qualitative	Qualitative content analysis

Platforms

This study compares two mature, developmental prototypes representing semi-automated and highly-automated simulated eVTOL platforms. Both aircraft had some augmentation, such as stability control, but significant differences existed for most features of flight.

Semi-Automated Platform.

In the semi-automated eVTOL platform, the manual controls (e.g., stick, throttle) were similar to conventional aircraft. While hovering, the aircraft flew like a helicopter; the pilot controlled direction and speed by manipulating the aircraft's attitude (e.g., pitch, roll, and yaw axes), and controlled altitude by manipulating power to lift rotors. In forward, wing-borne flight, the controls were similar to an airplane; thrust controlled airspeed, and the pilot manipulated the heading and altitude of the aircraft with pitch, bank, and yaw. This aircraft does not have decoupled axes; for example, a change in attitude would affect the aircraft's altitude while in hover. Further, it has no envelope protection (e.g., bank angle, rate of climb/descent).

Highly Automated Platform

While hovering in the highly-automated eVTOL platform, pilots controlled speed and altitude by making inputs to controls that were spring-loaded to the center. When the pilot's input was released, the aircraft would stop moving, whether in the vertical or horizontal plane. Envelope protections limited groundspeed and rate of climb and descent. The machine programmed and controlled the rates of acceleration, and deceleration while in forward, wing-borne flight. This machine control could be manipulated by the pilot to affect the rate at which the aircraft sped up or slowed down. Pilots controlled altitude by setting the desired pitch which the aircraft would hold when the controls were released. To turn the aircraft, the pilot had to hold it in a bank and the aircraft would return to a wings-level attitude when the pilot released the controls. Envelope protections while wing-borne limited bank and pitch angles to prevent stalling (see Figure 2 below for a high-level description of both platforms and Appendix A for a full description of automated features).

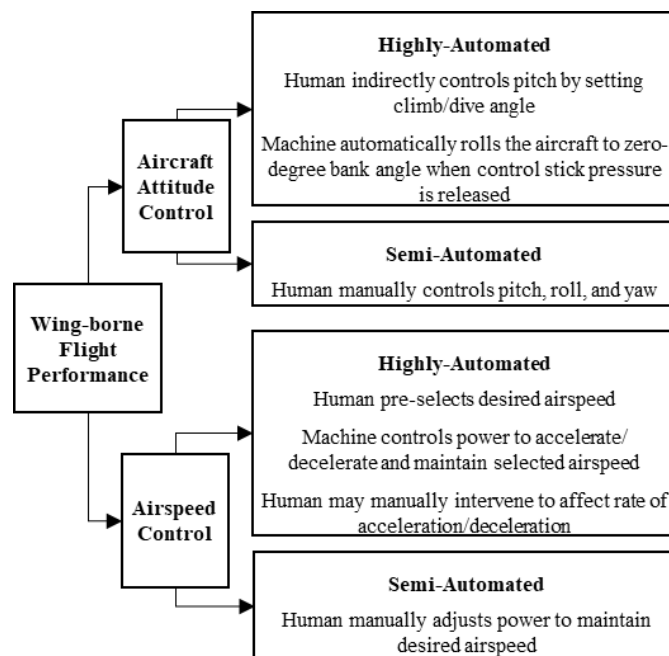


Figure 2. Aircraft Automation Comparison

Flight Profile

Participants viewed a training video that briefly described the unique aspects of their assigned eVTOL aircraft, an overview of its controls, and a preview of the full flight profile. The training video covered the content necessary to get pilots into the simulator to explore learnability and did not represent future training programs. Finally, participants flew the 20- to 30-minute flight profile four times. The flight profile simulated the Washington D.C. area and included easily identifiable landmarks (Appendix E). It consisted of six profile segments, or legs, four of which included wing-borne flight. Each leg covered a variety of eVTOL flight maneuvers, including takeoffs, enroute navigation (including shifts in altitude and turns), and approaches and

landings. Instructor Pilots (IPs) guided participants through each repetition of the profile, providing both instruction and simulated air traffic control (ATC) commands. IPs provided scripted ATC commands and basic flight guidance; IPs followed the script as closely as possible but were allowed to deviate when participant performance demanded additional or alternative input. During the first repetition of the flight profile, IPs gave additional, individualized coaching beyond the script to address the needs that emerged for each participant. During the second and third repetitions, the only additional instructional input provided were reminders from the script for the correct airspeed, heading, altitude, and path as needed. During the fourth repetition, IPs provided ATC commands only, with no additional scripted or unscripted guidance. Participants took a post-survey after completing all repetitions.

Measures

Demographic data collected includes flying experience, age, and education level. In addition to demographic information, researchers collected participant performance data from simulator systems and instructor evaluations. Multiple-choice tests were to measure only the flying knowledge the participants gained in the performance scenarios. A standardized grading tool (SPOTLITE) was used to improve inter-rater reliability of participant performance evaluations. PETS compares the position, attitude, and velocity of the exemplar aircraft flight and the participants' performance. The PETS analysis evaluates phases of the flight profile in which the participant demonstrated predetermined competencies. Evaluators observed participant performance to provide subjective evaluations of participant performance using the SPOTLITE evaluation tool. Neutral observers administered standardized exit interviews using questionnaires (Fowler & Mangione, 1990).

Demographic Questionnaire

The demographic questionnaire is at Appendix A. It is designed to quantify demographic factors such as age, hours of flying experience, hours of aircraft simulator experience, hours of unmanned aerial systems experience, and interest in flying activities. This data is combined with demographic data from electronic systems including aptitude test scores, and education level. Standardized instructions to the evaluators will ensure the questionnaire is administered consistently, and to minimize evaluator influence on participant answers.

Cognitive and Psychomotor Resource Availability

The subjects resource availability was measured using a battery of cognitive and psychomotor tests that are shown to predict pilot performance. Perceptual integration capacity is measured using concealed words and snowy pictures. Math speed, accuracy, and throughput is measured using the ANAM software package. As is spatial orientation accuracy and throughput. Cognitive switching is measured by switching between math and spatial orientation tasks. Multi-arm coordination, accuracy, and throughput are measured using a two-arm pantograph device. Evaluators rated participant performance using a 4-point scale derived from AFI 11-202 Vol 2. Researchers selected this scale because the evaluators had many 'years' experience using this

rating system and it was well understood by all evaluators. The evaluators coded performance as 1(unsafe), 2 (major discrepancies), 3 (minor discrepancies), and 4 (proficient).

Post data collection discussion revealed that the four-category system of measuring students' performance failed to capture the differences in interval distance within categories. Researchers employed a modified Delphi method with 3 of the 5 expert evaluators. (Skulmoski et al., 2007) detail that a classic Delphi method recommends the anonymity of participants during the iteration. This was impossible as all evaluators worked closely and were the only ones evaluating participants. Conflicting schedules made it infeasible to have all five evaluators who participated in the trials. One evaluator was not in town during the exchange, and one was unavailable, having returned to his instructor duties. The three remaining evaluators completed 85% of the total scoring for both A and B devices. The three evaluators were given a single sheet of paper with an identical line weighted at one end with "1" and at the other end with "20." They were first told to identify where their perception of the categories was bounded by using a perceived competency rating, with "20" being full competency and "1" being no competency. Two of the three evaluators had near identical bounds on the four different categories, while one evaluator had similar categories for "unsafe", and "major discrepancies", but had a larger "minor discrepancy" category. A moderator guided the three evaluators to discuss their differences in ratings including key points that delineated between proficiency and excellence within the categories. After accounting for feedback given to the subjects, the evaluators settled on bounds for each category. The "unsafe category was the smallest category range and the least weighting as the evaluators agreed that coaching played a factor. Proficient also was a small category range with the highest weighting. Evaluators felt that to be proficient meant they would be comfortable letting the participant fly the device solo. The delineations between major and minor discrepancies constituted the majority of the conversation. Ultimately the three evaluators came to a consensus on initial weightings for the major and minor discrepancies categories. Once the initial category ranges were established, the evaluators then were asked, "if you had to assign a number for each category, what number would you assign?" This caused a second iteration and further evaluation of the first defined categories.

This discussion had the evaluators tried to identify one number for each category that best represented the performance within the specified range. Of note, the Major and Minor discrepancy ranges were adjusted. Minor discrepancy ranges were decided to be larger as there was a large variance of performance errors that constituted minor discrepancies. Major discrepancy ranges were consolidated slightly as the evaluators felt those more egregious errors were less common and more succinct. Through discussion, the category ranges were first further adjusted to the final ranges in Table 4.

The evaluators then discussed assigning a single number to each category. The unsafe category was first discussed. The evaluators agreed that assigning it a "2" satisfactorily captured unsafe performance. Proficient was the next level identified. The evaluators decided the lower end of the range captured both proficient and excellent perceived competencies and scored it as a "16." More discussion centered around major and minor discrepancy categories. Ultimately the evaluators adjusted the weighting around the midpoint of each of these ranges. For major discrepancies, they rounded to the lower end of the midpoint or "5" and for minor discrepancies rounded to the upper end of the midpoint or "13."

Table 4. Expert Consensus of Category Bounds

	Unsafe	Major Discrepancies	Minor Discrepancies	Proficient
Range	1-2	3-8	9-15	16-20
Weighted Point	2	5	13	16

Evaluators assessed data from both highly-automated and semi-automated platforms for inclusion criteria and removed participants that did not include all four sessions from the data set. Reasons for removing participants included motion sickness and/or simulator malfunction. Four participants were removed (4185, 9730, 7834, and 4197) from the Platform A data set due to missing sessions. This included three ab initio participants and one rated pilot. Five total participants were removed (3743, 5338, 1402, 7191, 9747) from the Platform B data set. This group included four Ab Initio participants and one rated pilot.

Missing data for both Platforms was input using the median value for that task. Nineteen data points from Platform A and 33 data points from Platform B were imputed using the median value for the individual task (Cugnata & Salini, 2017; Khan & Hoque, 2020). If a median value was 2.5 or 3.5, the imputed value was rounded up to the nearest whole number. The data was then coded in excel according to the expert weights.

Prior to the start of the training videos, participants went through a series of psychomotor tests. The tests were developed in conjunction with the USAF Test Pilot school. These basic performance resources (BPRs) were designed to provide a comprehensive and holistic picture of the participant at the time of the simulator sessions. Each participant's BPRs were transcribed from individual excel files onto a master excel sheet. Once transcribed, the data was transferred into SPSS 28 for further analysis.

Performance Grading

Participants flew a standard flight scenario allowing researchers to assess a subset of flying competencies. Competencies are defined in a master competency list describing cognitive, psychomotor, and affective outcomes grouped into complex patterns of behaviors. Each competency may consist of many tasks and subtasks the participant must perform during the scenario presented. The competencies assessed are the same for all simulators used in the experiment.

Spotlight

Instructor pilots (IPs) acted as Air Traffic Control (ATC) for all flight repetitions. IPs provided primarily scripted instruction to help the participants and only deviated from the script when the participant required additional feedback. IPs provided scaffolded feedback, providing less feedback with each repetition of the profile; the final repetition of the flight profile provided only Air Traffic Control (ATC) commands. IPs rated each maneuver within the legs on a scale from 1 to 4 (1 = dangerous performance; 2 = major deviations; 3 = minor deviations; 4 = proficient performance). Researchers analyzed expert ratings to evaluate the effects of automation and experience.

Evaluators used a standardized observation tool to gauge subjective aspects of participant performance. The SPOTLITE tool provided a standardized set of observations that correlate to phases of flight. SPOTLITE observations are at Appendix B.

Performance Evaluation Training System (PETS)

Systems-based data were captured continuously from the flight simulators; the simulators (built by different companies) sampled data at different rates: 10 Hz for the highly automated platform and 95 Hz for the semi-automated platform. Researchers focused on airspeed (in knots) and altitude (in feet) performance during wing-borne legs for each participant's first and fourth repetitions of the flight profile. Airspeed and altitude data from the first repetition provided a snapshot of how well pilots could fly each platform with minimal training, based only on their experience with fixed-wing aircraft. In contrast, airspeed and altitude data from the fourth repetition provided information on how much their performance improved after approximately two hours of experience flying in the simulator. Researchers analyzed systems-based data to evaluate the airspeed and altitude control during wing-borne flight and heading and acceleration control during landings. A data collection and analysis tool (PETS) was used to analyze performance using simulator outputs. The simulator programs output standardized data streams for analysis including: time/date, latitude, longitude, altitude, velocity (x,y,z), acceleration (x,y,z), heading, pitch, and roll. The PETS system compared position and velocity data from participants' first and fourth runs. The PETS system displays the difference between exemplar flights and participant performance.

Impressions of Performance and Learnability

Participants answered seven questions related to their experience during the study via the post-study Qualtrics questionnaire, provided once the participants had finished the flight. The exit interview is at Appendix G.

Protection of Human Subjects

Each participant in the study signed an informed consent letter (see Appendix B) stating that they will not be compensated for participating in the study, that their data will remain confidential to those administering the study, and that no personally identifiable information will be maintained by the researchers. Informed consent letters will be kept on file for 3 years.

An Air Force Institutional Review Board reviewed the research plan in accordance with AFI 40-402 and provide guidance to protect participants from physical or psychological harm as a result of the research. The Air Force Component Office of Human Research Protections determined the research to be exempt from institutional review board requirements (see Appendix C).

Data Collection Procedures

Participant's demographic, test, and performance data were anonymized and recorded in an Excel spreadsheet. Participants' exit interviews were anonymized and entered into a text file for further analysis. Raw data from SPOTLITE, tests, and exit interviews were destroyed once

entered into the data analysis tools. No data containing personal information was retained after it is recorded in the data analysis tools.

Data Analysis Procedures

Anonymized quantitative data were analyzed using a variety of statistical tools and processes.

Results

Psychomotor Capacity of Participants

Prior to the start of the training videos, participants went through a series of psychomotor tests. The tests were developed in conjunction with the USAF Test Pilot school. Researchers designed these basic performance resources (BPRs) to get a comprehensive and holistic picture of the participant at the time of the simulator sessions.

Comparing performance between platforms

An independent t-test revealed that participants did not have similar performance in the two devices. All maneuvers showed a statistically significant difference in performance ($p < .05$) between subjects operating the two aircraft simulators.

Table 5. T-test results for comparison of performance in simulators

Performance	t	p
Leg1_Hover	t(72)=5.68	<.001
Leg2_Hover	t(72)=8.06	<.001
Leg3_Takeoff*	t(68.16)=3.9	.013
Leg3_EnRoute	t(72)=2.356	.021
Leg3_ApprLand*	t(56.27)=3.955	<.001
Leg4_Takeoff	t(72)=3.118	.003
Leg4_EnRoute*	t(66.851)=2.327	.023
Leg4_ApprLand*	t(50.331)=4.733	<.001
Leg5_Takeoff*	t(68.296)=4.194	<.001
Leg5_EnRoute	t(72)=3.01	.004
Leg5_ApprLand*	t(67.799)=2.46	.016

* equal variances not assumed using 'Levene's test

Comparing performance between participants

There were significant differences between ab initio participants and rated pilots on all performance measures except for Leg2_Hover. While a difference did exist between the two

groups during Leg1_Hover, performance measures on Leg2_Hover were not significantly different. This was not indicative of quick learning of devices because the two profiles for the hover were composed of different flight patterns. Leg1_Hover was maintaining a hover while taxiing while Leg2_Hover required participants to follow a square pattern over a specific area. These two flight profiles were too different to compare.

Table 6. T-test results for Ab Initio and Rated Pilot Performance

Performance	t	p
Leg1_Hover	t(72)=2.386	.02
Leg2_Hover	t(72)=1.118	.267
Leg3_Takeoff*	t(65.804)=3.762	<.001
Leg3_EnRoute	t(72)=4.615	<.001
Leg3_ApprLand*	t(59.18)=3.675	<.001
Leg4_Takeoff	t(72)=3.361	.001
Leg4_EnRoute*	t(67.266)=5.42	<.001
Leg4_ApprLand*	t(67.846)=3.246	.002
Leg5_Takeoff*	t(64.616)=4.485	<.001
Leg5_EnRoute	t(72)=5.036	<.001
Leg5_ApprLand*	t(56.273)=5.193	<.001

* equal variances not assumed using 'Levene's test

We then evaluated participants BPR measurements to determine if a difference existed between Ab Initio and Rated Pilots. Differences existed on BRP 17 and BPR 36 between the two groups. BPR 36 was flight experience, which was expected to be different. Thus, ultimately only BPR 17 (Working memory, time) was shown to be statistically different between the two groups.

Testing the data

Researchers tested the combined dataset for each performance measure for assumptions of normality to meet the required assumptions of regression. All dependent variables were measured on a scale and contained independent variables and observations. Multicollinearity and homoscedasticity were evaluated in each model. Only "Leg5_ApprLand" did not meet assumptions for normality. Researchers determined that two high-performing outliers skewed the data, however they were left in for the analysis.

Testing for BPRs that Predict eVTOL Performance

Table 7 lists the BPR code, apparatus used to measure the BPR, what the apparatus was measuring, and scoring data. The lead researcher transcribed each participant's BPRs from individual excel files onto a master excel spreadsheet and then transferred the data into SPSS 28 for further analysis.

Table 7. Basic Performance Resources

No.	Basic Performance Resource	No.	Basic Performance Resource
1	ETS: Perceptual Integration Capacity (CW)	17	ANAM: Working Memory Throughput (Math Processing)
2	ETS: Perceptual Integration Capacity (SP)	18	ANAM: Spatial Orientation Speed (Manikin)
3	Change Detection (Flicker Test)	19	ANAM: Spatial Orientation Accuracy (Manikin)
4	Lafayette: MLC Speed	20	ANAM: Spatial Orientation Throughput (Manikin)
5	Lafayette: MLC Accuracy	21	ANAM: Cognitive Flexibility Speed (Switching)
6	Lafayette: MLC Throughput	22	ANAM: Cognitive Flexibility Accuracy (Switching)
7	Simon: Short Term Memory	23	ANAM: Cognitive Flexibility Throughput (Switching)
8	MOART Choice Reaction Time	24	ANAM: Pursuit Tracking Mean Distance (Motor Coordination)
9	MOART Choice Reaction Movement Time	25	ANAM: Pursuit Tracking Percent in Circle (Motor Coordination)
10	MOART Reaction Total Time	26	ANAM: Pursuit Tracking RMS Distance (Motor Coordination)
11	MOART Single Tap Maximum (30 sec)	27	Control Strength: Yaw Clockwise
12	ANAM: Procedural Reaction Time	28	Control Strength: Yaw Counterclockwise
13	ANAM: Procedural Reaction Accuracy	29	Control Strength: Roll Right
14	ANAM: Procedural Reaction Throughput	30	Control Strength: Roll Left
15	ANAM: Working Memory Speed (Math Processing)	31	Total Flight Hours (Experience)
16	ANAM: Working Memory Accuracy (Math Processing)	32	Gaming Annual Hours (Experience)

Researchers then ran stepwise regression using SPSS. BPRs 11, 31, 32, 35 and 38 were removed from the analysis because they were constants or had missing correlations. Table 8 depicts the BPR predictors for each performance using both devices.

Table 8. BPR Predictors of Performance for both simulators

Performance	R	R ²	Predictors	F	p
Leg1_Hover	.432	.187	BPR1, BPR3	7.57	.001
Leg2_Hover	.460	.188	BPR1, BPR3	8.88	<.001
Leg3_Takeoff	.486	.219	BPR2, BPR6, BPR29	6.083	.001
Leg3_EnRoute	.6	.36	BPR6, BPR16, BPR7, BPR1, BPR27	7.089	<.001
Leg3_ApprLand	.431	.186	BPR3, BPR9	7.531	.001
Leg4_Takeoff	.627	.393	BPR16, BPR22, BPR1, BPR6	10.37	<.001
Leg4_EnRoute	.355	.126	BPR16	9.689	.003
Leg4_ApprLand	.417	.174	BPR3, BPR1	6.94	.002
Leg5_Takeoff	.476	.227	BPR23, BPR1	9.671	<.001
Leg5_EnRoute	.397	.158	BPR22, BPR1	6.186	.003
Leg5_ApprLand*	.391	.153	BPR22, BPR9	5.956	.004

Although the BPRs in the table above were statistically significant ($p < .05$) none were strong predictors of performance. The researchers concluded there weren't any BPRs that were predictive of performance in eVTOLs as a class of aerial vehicles. ($R^2 > .5$).

Testing for Platform-Specific BPRs

Low model fit prompted further evaluation into platform-specific BPR predictors. A separate regression analysis was conducted using simulator for the highly automated platform only the results of which are in table 9.

Table 9. BPR Predictors of Performance for the Highly-Automated platform

Performance	R	R ²	Predictors	F	p
Leg1_Hover	.404	.163	BPR3	5.86	.02
Leg2_Hover	.545	.297	BPR3, BPR2	6.112	.006

Leg3_EnRoute	.578	.334	BRP6, BPR3	7.277	.003
Leg3_ApprLand	.611	.373	BPR3, BPR9, BPR21	5.552	.004
Leg4_EnRoute	.362	.131	BPR3	4.534	.042
Leg4_ApprLand	.380	.145	BPR3	5.078	.032
Leg5_Takeoff	.384	.147	BPR17	5.174	.03
Leg5_EnRoute	.449	.201	BPR22	7.555	.01

Although the BPRs in the table above were statistically significant ($p < .05$) none were strong predictors of performance ($R^2 > .5$). The researchers concluded there weren't any BPRs that were predictive of performance in the highly-automated eVTOL platform. Researchers conducted a separate regression analysis using the semi-automated platform's data only.

Table 10. BPR Predictors of Performance for the Semi-Automated platform

Performance	R	R ²	Predictors	F	p
Leg1_Hover	.598	.358	BPR4, BPR5, BPR6	6.13	.002
Leg2_Hover	.662	.438	BRP18, BPR27, BPR16, BPR21	6.234	<.001
Leg3_Takeoff	.405	.164	BPR36	6.875	.013
Leg3_EnRoute	.861	.741	BPR16, BPR7, BPR27, BPR1, BPR34, BPR12	14.279	<.001
Leg3_ApprLand	.86	.739	BRP9, BPR15, BPR16	31.198	<.001
Leg4_Takeoff	.857	.735	BPR16, BPR12, BPR14, BPR4, BPR2, BPR29	13.886	<.001
Leg4_EnRoute	.792	.628	BPR36, BPR16, BPR3	18.532	<.001
Leg4_ApprLand	.506	.256	BPR16, BPR5	5.838	.007
Leg5_Takeoff	.729	.531	BPR16, BPR36, BPR21, BPR1	9.055	<.001
Leg5_EnRoute	.848	.719	BP9, BPR24, BPR34, BPR27, BPR5, BPR29, BPR16, BPR1, BPR10, BPR23, BPR25	5.819	<.001
Leg5_ApprLand	.644	.415	BPR9, BPR4	12.054	<.001

The significant BPRs in the table above ($p < .05$) several were strong predictors of performance ($R^2 > .5$). Several BPRs predicted performance in multiple maneuvers. The researchers concluded there were several BPRs that predicted performance in portions of the flight profile in

the semi-automated eVTOL. The quantity of maneuvers that each BPR was significant is listed in table 11.

Table 11. Frequency of BPRs as Predictors of Performance

Count (B)	Predictors (B)
1	BPR2, BPR3, BPR6, BPR7, BPR10, BPR14, BPR15, BPR18, BPR23, BPR24, BPR25
2	BPR5, BPR12, BPR21, BPR29, BPR34
3	BPR1, BPR4, BPR9, BPR27, BPR36
8	BPR16

Analysis of the combined devices yielded weak models, suggesting that there were no basic performance resources that predicted performance in eVTOLs as a class of aerial vehicle. An individual analysis by simulator found significant predictors existed for the highly-automated platform, however the models were not strong. Researchers found significant BPR predictors and strong models for the semi-automated platform. As automation in the machine increased the demand for human resources decreased in ways that were both significant and effectual.

Performance of Participants in Simulated Flight Operations

A summary of the results of the growth curve analyses, including the intercept (baseline performance), linear coefficient (slope), and quadratic coefficient (change in slope where applicable) for each maneuver is displayed in Table 12.

Table 12. Growth Curve Analysis Summary by Platform

	Intercept	Linear Coefficient	Quadratic Coefficient
Highly Automated Platform			
Hover	3.37	0.20	NA
Takeoff	NA	NA	NA
Enroute Navigation	3.21	0.52	-0.09
Approach and Landing	2.94	0.25	NA
Semi-Automated Platform			
Hover	2.45	0.20	NA
Takeoff	3.12	0.21	NA
Enroute Navigation	2.71	0.52	-0.06
Approach and Landing	2.08	0.35	NA

a for all reported polynomial trends, $p < .001$. *b* growth curve analyses could not be conducted for takeoff maneuvers in the highly automated platform because no variance was observed between participants in the third repetition of the flight profile.

Hover Maneuvers

For hover maneuvers (see Table 12. Growth Curve Analysis Summary by Platform and Figure 3), participant baseline performance in the highly-automated platform was significantly higher than for participants in the semi-automated platform (highly-automated = 3.37; semi-automated = 2.45, $p < .001$). This suggests that greater levels of automation led to better hovering performance.

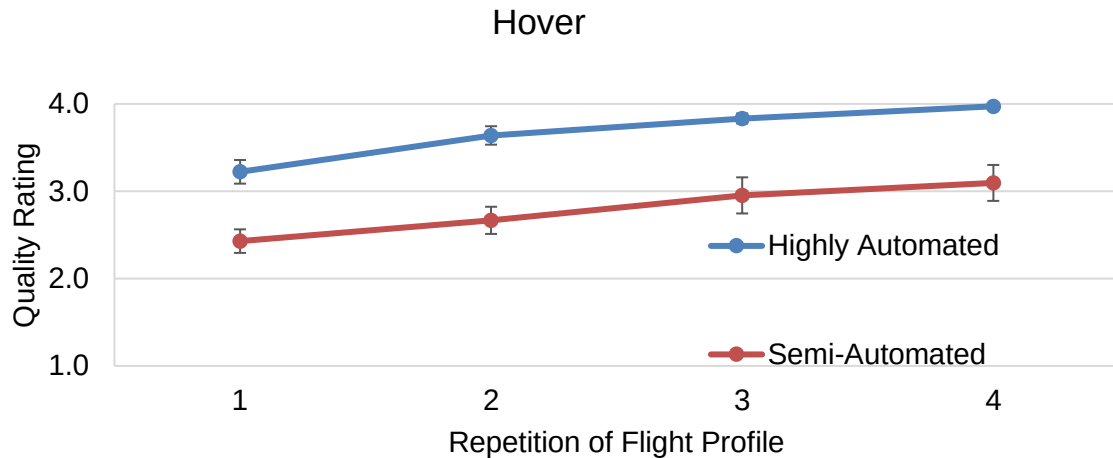


Figure 3. Learning Trajectories for Hover Maneuvers

There was a significant linear effect for the learning trajectory ($b = 0.20$, $p < .001$). This learning trajectory did not differ between the two platforms and was not affected by baseline performance. This indicated that learners grew in hover proficiency at similar rates, regardless of which platform they were assigned to and how high their baseline performance was. If this same trajectory continued for repetitions of the flight profile beyond the duration of the study, we would expect participants in the highly-automated platform to have mastered basic hovering after four repetitions of the flight profile, and participants in the semi-automated platform to have mastered hovering after eight repetitions of the flight profile.

Takeoff

For takeoff maneuvers (see Table 11. Growth Curve Analysis Summary by Platform and Figure 4) in the highly-automated platform, all participants reached ceiling levels by the third repetition of the flight profile. Because there was no variability, growth curve analyses could not be performed. However, this result does indicate that three repetitions of the profile were sufficient for participants to master basic eVTOL takeoff in this platform.

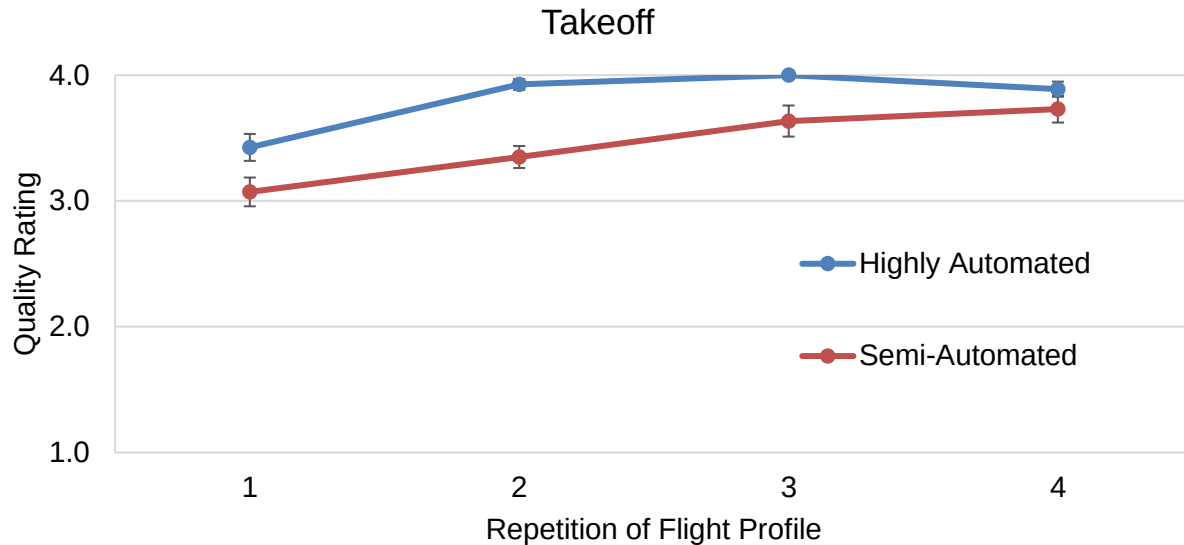


Figure 4. Learning Trajectories for Takeoff Maneuvers

Participants in the semi-automated platform had a baseline performance of 3.12 and a significant linear growth trajectory of 0.21 ($p < .001$). If this same trajectory continued for repetitions of the flight profile beyond the duration of the study, we would expect participants in the semi-automated platform to have mastered takeoff in six repetitions of the flight profile.

Enroute Navigation

For enroute navigation (see Table 11. Growth Curve Analysis Summary by Platform and Figure 5), participants in the highly-automated platform achieved a significantly higher baseline level of performance than participants in the semi-automated platform (*highly-automated* = 3.21; *semi-automated* = 2.71, $p < .001$). This suggests that greater levels of automation led to better performance during enroute navigation. There was a significant linear effect for the learning trajectory ($b = 0.52$, $p < .001$). This learning trajectory did not differ between the two platforms and was not affected by the baseline levels of performance. There was also a significant quadratic effect. This effect differed significantly between the platforms (*highly-automated* = -

.091; for *semi-automated* = -.064).

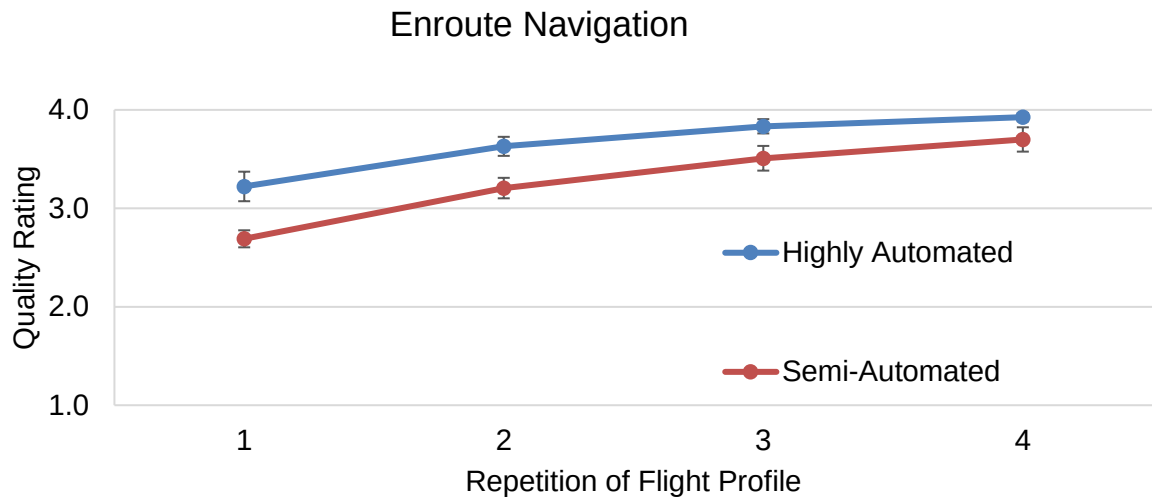


Figure 5. Learning Trajectories for Enroute Navigation

These learning trajectories indicated that learners grew in proficiency at similar rates; however, each repetition of the profile resulted in smaller gains for participants in the highly-automated platform than for participants in the semi-automated platform. If this same trajectory continued for repetitions of the flight profile beyond the duration of the study, we would expect participants in the highly-automated platform to have mastered enroute navigation after four repetitions of the flight profile. For participants in the semi-automated platform, we would expect their performance to plateau after the fourth repetition while approaching a rating of 4.0.

Approach and Landing

For approach and landing (see Table 11. Growth Curve Analysis Summary by Platform and Figure 6), participants in the highly-automated platform achieved significantly higher baseline levels of performance than participants in the semi-automated platform (highly-automated = 2.94; semi-automated = 2.08, $p < .001$). This suggests that greater levels of automation led to better performance on approach and landing maneuvers.

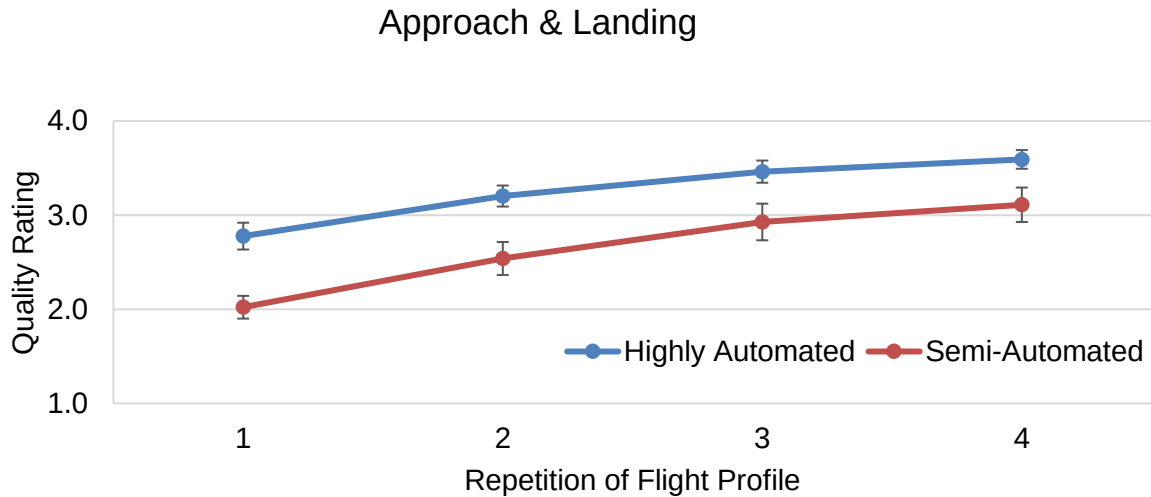


Figure 6. Learning Trajectories for Approach & Landing

Researchers observed a significant linear effect for the learning trajectory that differed between platforms. The learning trajectory for the highly-automated platform was 0.25 ($p < .001$); in contrast, the learning trajectory for the semi-automated platform was 0.35 ($p < .001$). This indicates that learners grew in proficiency faster in the semi-automated platform than in the highly-automated platform. Based on this trajectory, we would expect experienced pilots learning the highly-automated platform to have mastered approach and landing after six repetitions of the flight profile and experienced pilots learning the semi-automated platform to have mastered approach and landing maneuvers after seven repetitions of the flight profile.

Learning Trajectories of Pilots and Ab Initio Participants

Each prototype aircraft used in this study has varying degrees of, and approaches to Simplified Vehicle Operations (SVO), such as stability, airspeed, and altitude. According to Martos and Duerkson (2021) “SVO is the use of automation coupled with human factors best practices to reduce the quantity of trained skills and knowledge that the pilot or operator of an aircraft must acquire to operate the system at the required level of operational safety.” Manufacturers claim that compared to the operations of conventional aircraft, the SVO features present in eVTOLs will make them easier to operate, with the expectation that automation will decrease pilot workload, increase safety, and reduce training times (General Aviation Manufacturers Association, 2019).

Semi-Automated Platform

Table 13 Summary of Results for Flight Proficiency by Pilot Type in the Semi-Automated Platform

	Intercept	Linear Coefficient	Quadratic Coefficient
Rated Pilots			

Hover	2.44	.274	
Takeoff	3.11	.210	
Enroute Navigation	2.70	.576	-.08
Approach & Landing	2.02	.610	-.08
Ab Initio			
Hover	1.97	.274	
Takeoff	2.59	.210	
Enroute Navigation	2.16	.460	-.08
Approach & Landing	1.59	.610	-.13

*For all reported polynomial trends $p < .001$

Hover Maneuvers

For hover maneuvers (see Table 13 and Figure 7), participants' baseline performance in the semi-automated platform was significantly higher for rated pilots than in ab initio participants (rated pilots = 2.44; ab initio = 1.97, $p < .001$). This suggests that more experienced pilots had a higher baseline proficiency for hovering than inexperienced pilots. There was a significant linear effect for the learning trajectory ($b = 0.274$, $p < .001$). This learning trajectory did not differ between the two groups and was unaffected by baseline performance.

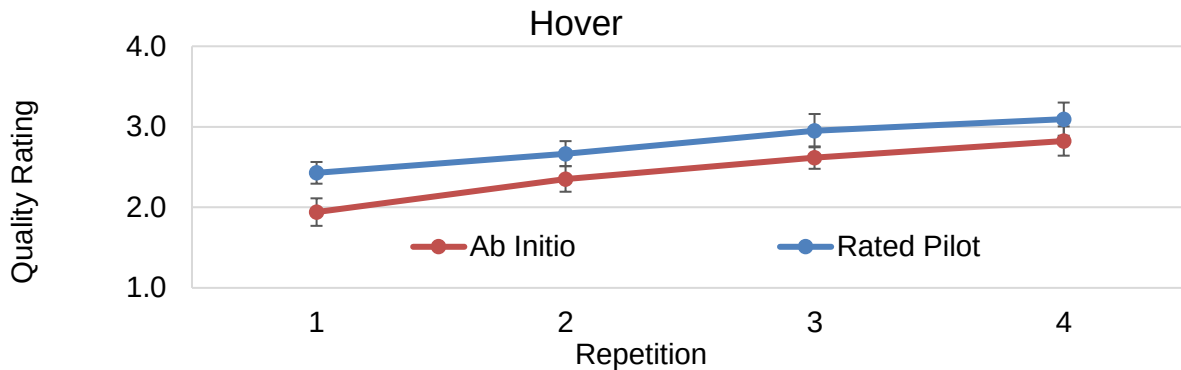


Figure 7. Learning Trajectories by Pilot Type for Hover in a Semi-automated eVTOL

This result indicates that both groups of learners grew in proficiency at similar rates, regardless of previous flight experience and regardless of how high their baseline performance. If this same trajectory continued for additional repetitions of the flight profile beyond the duration of the study, we would expect that rated pilots in the semi-automated platform to have mastered hovering after six repetitions of the flight profile (i.e., 12 hover maneuvers; approximately three hours) and ab initio pilots in the semi-automated platform to have mastered hovering after eight repetitions of the flight profile (i.e., 16 hover maneuvers; approximately four hours).

Takeoff

For takeoff maneuvers (see Table 13 and Figure 8), participants' baseline performance in the semi-automated platform was significantly higher for rated pilots than ab initio participants (rated

pilots = 3.11; *ab initio* = 2.59, $p < .001$). This result suggests that more experienced pilots had a higher baseline proficiency for taking off than inexperienced pilots. There was a significant linear effect for the learning trajectory ($b = 0.210$, $p < .001$). This learning trajectory did not differ between the two groups and was unaffected by baseline performance.

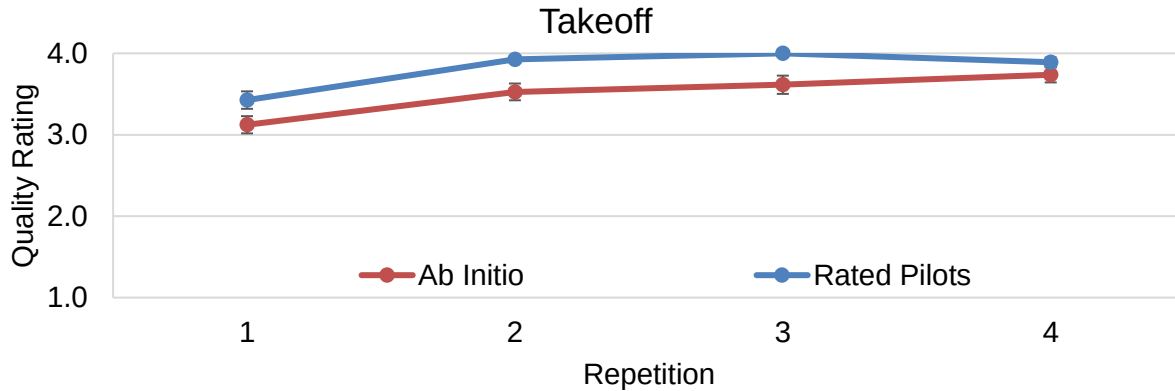


Figure 8. Learning Trajectories by Pilot Type for Takeoff in a Semi-automated eVTOL

This indicates that learners grew in proficiency at similar rates, regardless of previous flight experience and their baseline performance. If this same trajectory continued for additional repetitions of the flight profile, we would expect rated pilots in the semi-automated platform to have mastered taking off after four repetitions of the flight profile (i.e., 12 takeoff maneuvers; approximately two hours) and *ab initio* pilots in the semi-automated platform to have mastered hovering after seven repetitions of the flight profile (i.e., 21 takeoff maneuvers; approximately three and a half hours).

Enroute Navigation

For enroute navigation (see Table 13 and Figure 9), participants' baseline performance in the semi-automated platform was significantly higher for rated pilots than in *ab initio* participants (*rated pilots* = 2.70; *ab initio* = 2.16, $p < .001$). This result suggests that more experienced pilots had a higher baseline proficiency for enroute navigation than inexperienced pilots. There was a significant linear effect for the learning trajectory in rated pilots ($b = 0.576$, $p < .001$). *Ab initio* pilots also had a significant linear effect on learning, although it differed from the rated pilots ($b = 0.460$, $p < .001$), demonstrating that learning progressed at a slower rate for *ab initio* than rated pilots. There was also a significant quadratic effect. This effect was the same between the groups ($q = -.08$, $p < .05$).

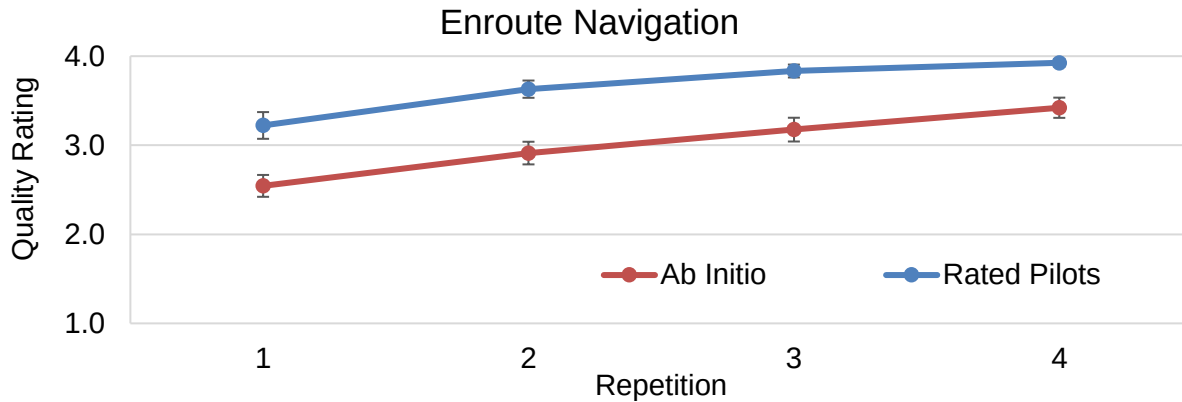


Figure 9. Learning Trajectories by Pilot Type for Enroute Navigation in a Semi-automated eVTOL

These learning trajectories indicate that learners grew in proficiency at different rates, with each repetition of the profile resulting in smaller gains for participants in both groups. If this same trajectory continued for additional repetitions of the flight profile, we would not expect either group of learners to become fully proficient without additional instruction, reaching their peak after the third repetition, with rated pilots leveling off just below a rating of 4.0 and ab initio pilots leveling off just below a 3.0.

Approach and Landing

For approaches and landings (see **Table 4** and **Figure 10**), participants' baseline performance in the semi-automated platform was significantly higher for rated pilots than for ab initio participants (*rated pilots* = 2.02; *ab initio* = 1.59, $p < .001$). This result suggests that more experienced pilots had a higher baseline proficiency for approaches and landings than inexperienced pilots. There was a significant linear effect for the learning trajectory ($b = 0.610$, $p < .001$). This learning trajectory did not differ between the two groups and was not affected by baseline performance. There was also a significant quadratic effect. This effect differed between the groups (*rated pilots* = $-.08$, $p < .05$, *ab initio* = $-.13$, $p < .05$).

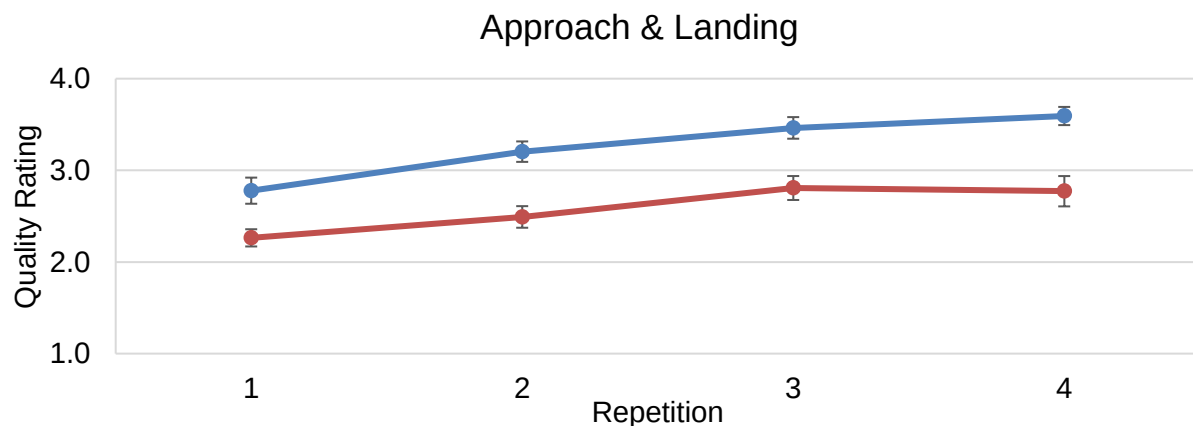


Figure 10. Learning Trajectories by Pilot Type for Approach & Landing in a Semi-automated eVTOL

These learning trajectories indicated that learners grew in proficiency at different rates, with each repetition of the profile resulting in smaller gains for participants in both groups, but even

more intensely in the ab initio group. If this same trajectory continued for additional repetitions of the flight profile, we would not expect either group of learners to become fully proficient without additional instruction, reaching their peak after the third repetition with rated pilots leveling off just above a rating of 3.0 and with ab initio pilots leveling off just above a rating of 2.0.

Highly Automated Platform

Table 14 Summary of Results for Flight Proficiency by Pilot Type in the Highly Automated Platform

	Intercept	Linear Coefficient	Quadratic Coefficient
Rated Pilots			
Hover	3.26	.431	-.07
Takeoff	3.44		
Enroute	3.45	.300	-.04
Navigation			
Approach & Landing	2.95	.239	
Ab Initio			
Hover	2.96	.431	-.07
Takeoff	3.10		
Enroute	2.55	.300	-.04
Navigation			
Approach & Landing	2.25	.239	

*For all reported polynomial trends $p < .001$

Hover Maneuvers

For hover maneuvers (see Table 14 and Figure 11), participants' baseline performance in the highly-automated platform was significantly higher for rated pilots than in ab initio participants (rated pilots = 3.26; ab initio = 2.96, $p < .001$). This suggests that more experienced pilots had a higher baseline proficiency for hovering than inexperienced pilots. There was a significant linear effect for the learning trajectory ($b = 0.431$, $p < .001$). This learning trajectory did not differ between the two groups and was unaffected by baseline performance. There was also a significant quadratic effect. This effect was the same between the groups ($q = -.07$, $p < .005$).

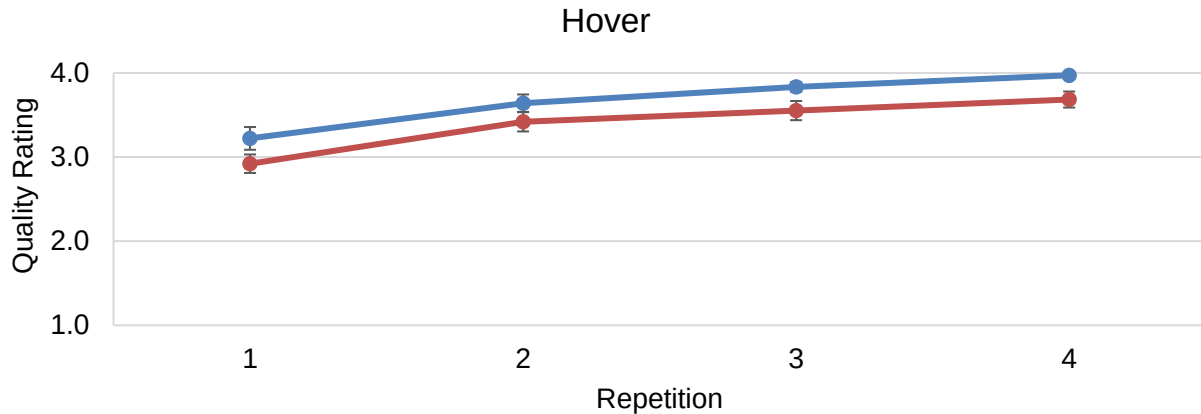


Figure 11. Learning Trajectories by Pilot Type for Hover in a Highly Automated eVTOL

This result indicated that learners grew in proficiency at similar rates, with each repetition of the profile resulting in smaller gains for participants, regardless of previous flight experience. If this same trajectory continued for additional repetitions of the flight profile, we would expect rated pilots in the highly-automated platform to have mastered takeoffs after three repetitions of the flight profile (i.e., six hover maneuvers, approximately an hour and a half) and ab initio pilots in the highly-automated platform would not reach full mastery without additional instruction but would instead plateau after the third repetition slightly below a rating of a 4.0.

Takeoff

For takeoff maneuvers (see Table 14 and Figure 12), participants' baseline performance in the highly-automated platform was significantly higher for rated pilots than ab initio participants (*rated pilots* = 3.44; *ab initio* = 3.10, $p < .01$).

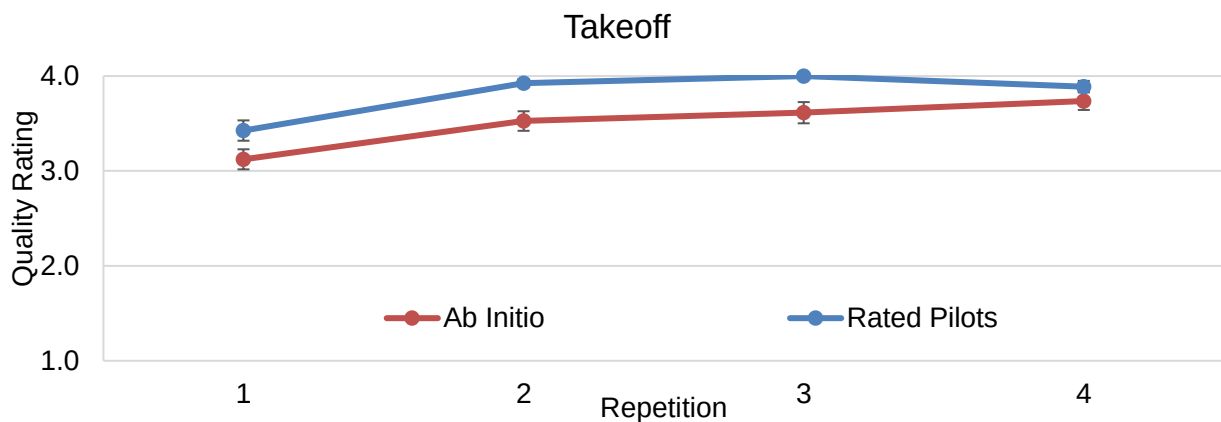


Figure 12. Learning Trajectories by Pilot Type for Takeoff in a Highly Automated eVTOL

All rated pilot participants reached ceiling levels of performance by the third repetition of the flight profile. Because there was no variability between rated pilots during this repetition, growth curve analyses could not be performed. However, this result does indicate that three repetitions of the profile were sufficient for participants to master takeoff in this platform. Ab initio pilots had a baseline performance of 3.18 and a significant linear growth trajectory of 0.18 ($p < .001$). If this

same trajectory continued for additional repetitions of the flight profile, we would expect ab initio pilots in the semi-automated platform to have mastered takeoff in the fifth repetition of the flight profile (i.e., 15 takeoff maneuvers; approximately two and a half hours).

Enroute Navigation

For enroute navigation (see Table 14 and Figure 13), participants' baseline performance in the highly-automated platform was significantly higher for rated pilots than in ab initio participants (rated pilots = 3.45; ab initio = 2.55, $p < .001$). This suggests that more experienced pilots had a higher baseline proficiency for enroute navigation than inexperienced pilots. There was a significant linear effect for the learning trajectory ($b = 0.300$, $p < .001$). There was also a significant quadratic effect for the rated pilots ($q = -.04$, $p < .001$). This quadratic effect was not significant for ab initio learners.

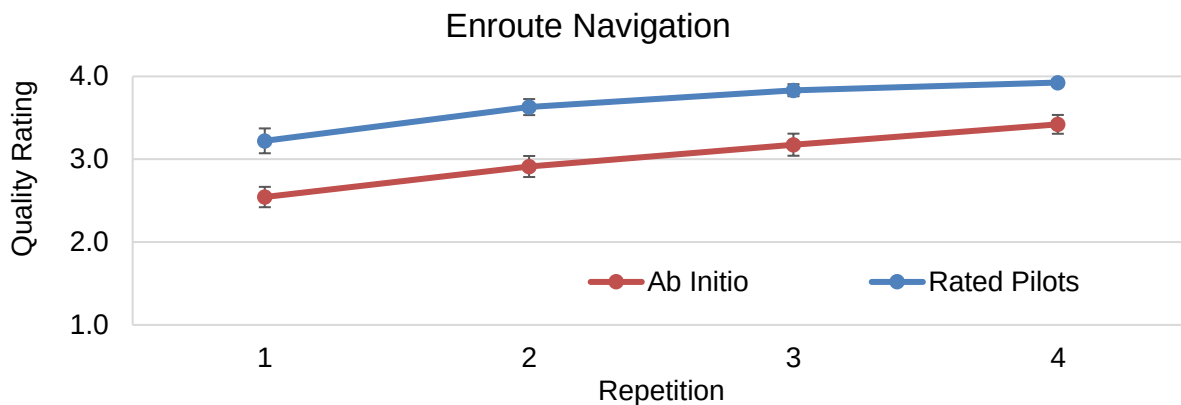


Figure 13.. Learning Trajectories by Pilot Type for Enroute Navigation in a Highly Automated eVTOL

These learning trajectories indicated that learners grew in proficiency at different rates, with each repetition of the profile resulting in smaller gains for rated pilots. If this same trajectory continued for additional repetitions of the flight profile, we would expect rated pilots in the highly-automated platform to have mastered enroute navigation after the fourth repetition of the flight profile (i.e., 12 enroute navigation maneuvers; approximately two hours), and ab initio pilots in the highly-automated platform would reach mastery after the fifth repetition (i.e., 15 enroute navigation maneuvers; approximately two and a half hours).

Approach and Landing

For approaches and landings (see Table 14 and Figure 14), participants' baseline performance in the highly-automated platform was significantly higher for rated pilots than in ab initio participants (rated pilots = 2.95; ab initio = 2.25, $p < .001$). This result suggests that more experienced pilots had a higher baseline proficiency for approaches and landings than inexperienced pilots. There was a significant linear effect for the learning trajectory ($b = 0.239$, $p < .001$).

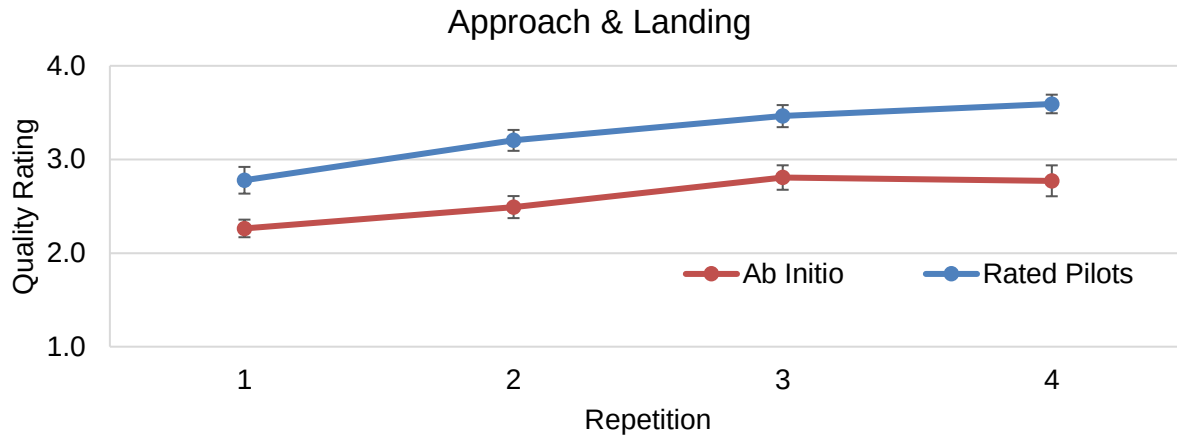


Figure 14. Learning Trajectories by Pilot Type for Approach & Landing in a Highly Automated eVTOL

This learning trajectory did not differ between the two groups and was not affected by baseline performance. This indicates that learners grew in proficiency at the same rates in both groups. If this same trajectory continued for additional repetitions of the flight profile, we would expect rated pilots in the highly-automated platform to have mastered approaching and landing after the fifth repetition of the flight profile (i.e., 15 approach and landing maneuvers, approximately two and a half hours), and ab initio pilots in the highly-automated platform would reach mastery after the eighth repetition (i.e., 24 approach and landing maneuvers; approximately four hours).

Performance Differences Between Fixed- and Rotary-Wing Pilots

This portion of the study explores how the learning profiles of pilots with rotary-wing experience differ from pilots with only fixed-wing experience when learning one of two eVTOL aircraft—one that was semi-automated and the other that was highly automated. Pilots repeated a pre-defined flight profile four times. Researchers compared data from five rotary-wing pilots in each platform to the averaged performance of fixed-wing pilots in the same eVTOL platform (semi-automated=16; highly automated=13).

Figure 15. Rotary Wing Pilots in Hover

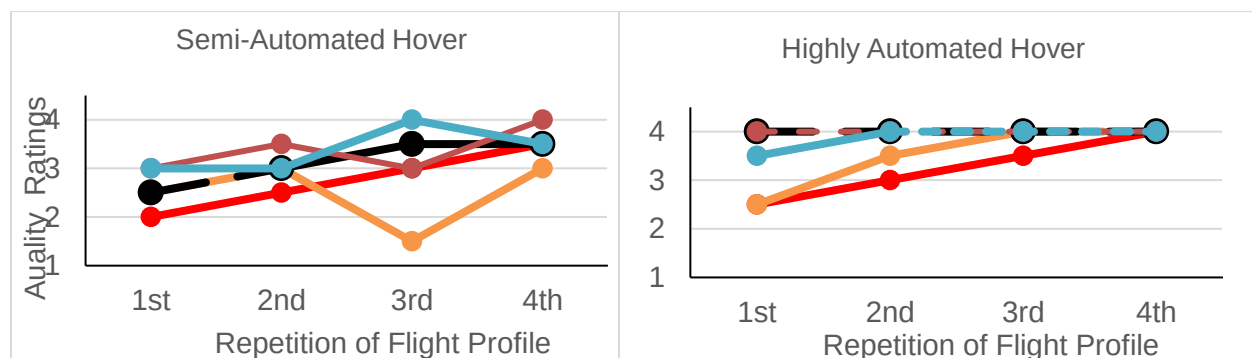


Figure 16. Fixed Wing Pilots in Hover

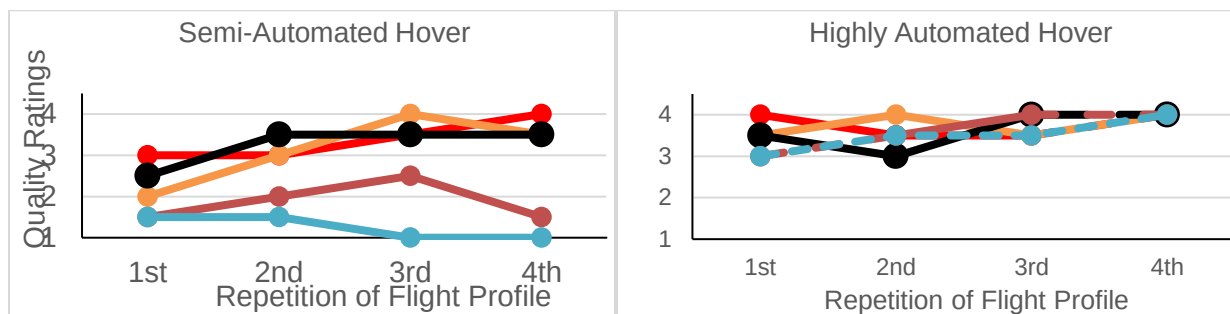


Figure 17. Rotary Wing Pilots in Takeoff

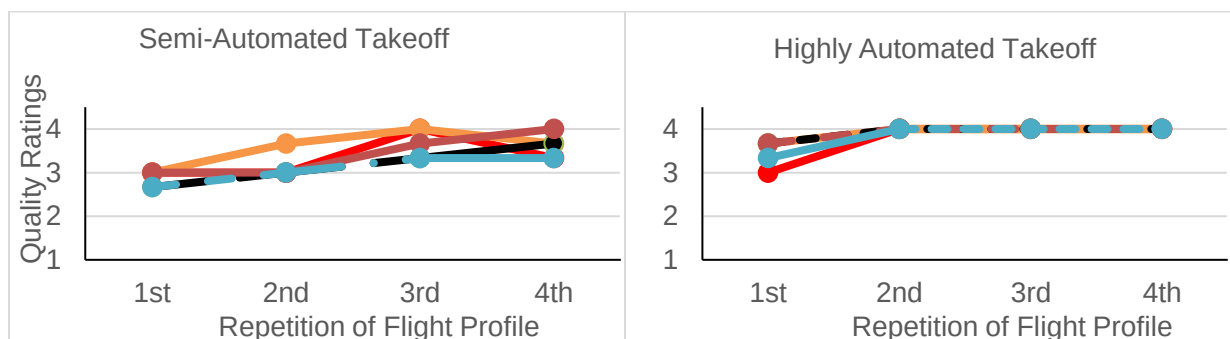


Figure 18. Fixed Wing Pilots in Takeoff

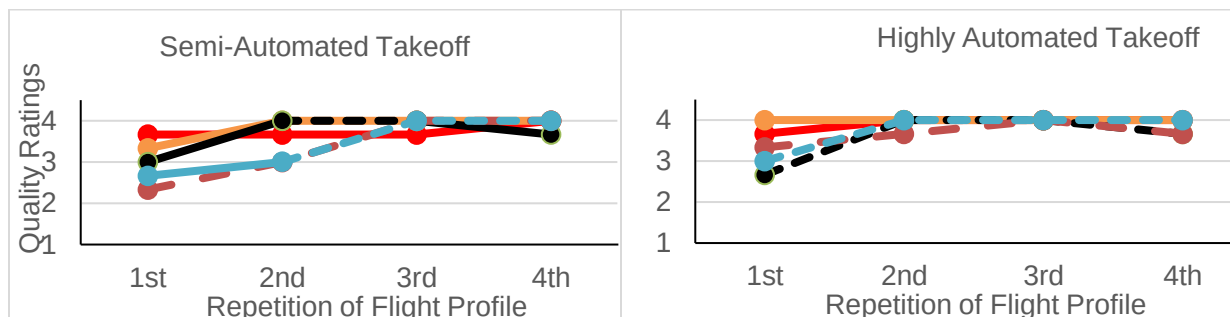


Figure 19. Rotary Wing Pilots in Enroute Navigation

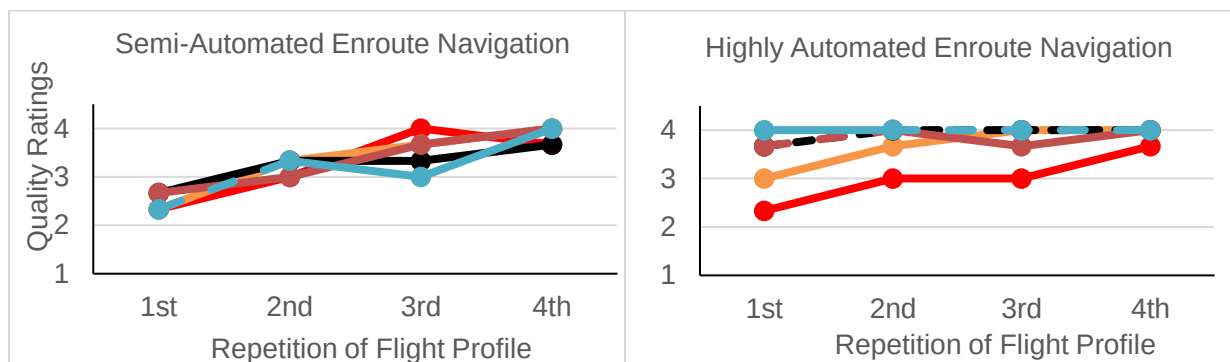


Figure 20. Fixed Wing Pilots in Enroute Navigation

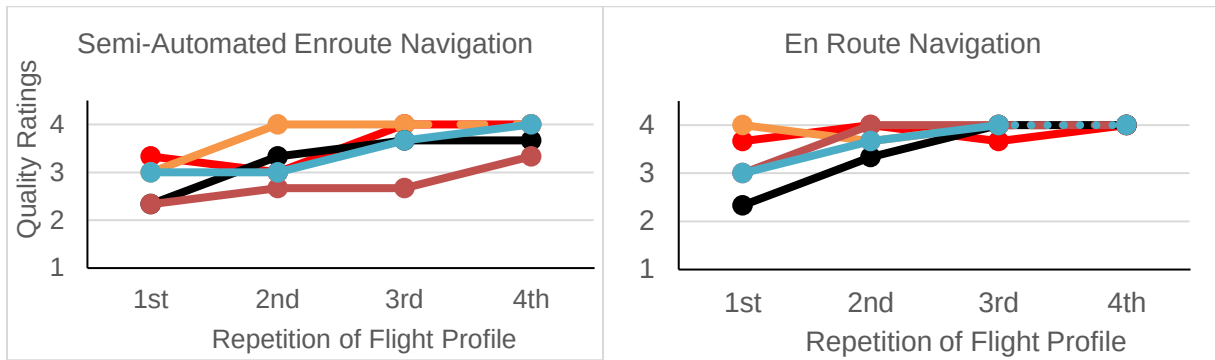
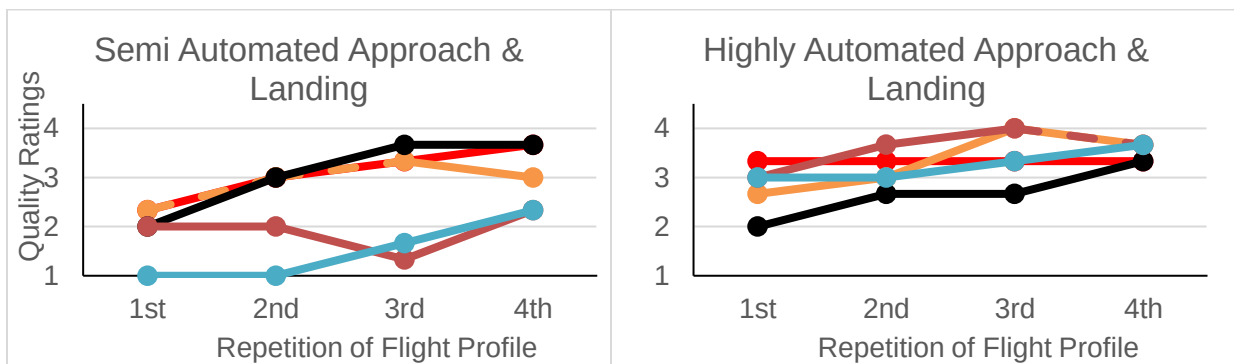


Figure 21. Rotary Wing Pilots Approach and Landing



Figure 22. Fixed Wing Pilots Approach and Landing



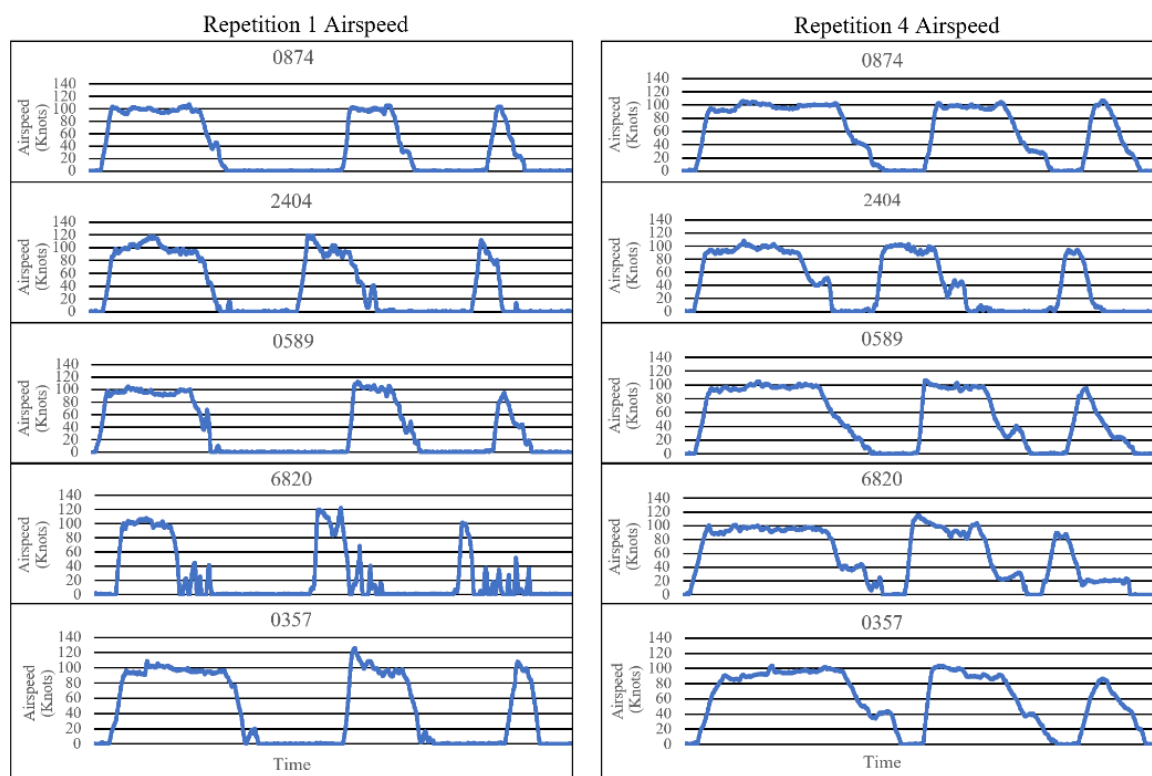
For the semi-automated platform, rotary-wing pilots had a slight but continuous advantage in hovering when compared to fixed-wing-only pilots. They also outperformed on enroute navigation and approach and landing maneuvers by the fourth repetition but were slightly behind their peers on takeoff maneuvers. For the highly automated platform, researchers noted few differences between rotary-wing and fixed-wing-only pilots due in part to both groups reaching performance ceilings on many maneuvers. Overall, results revealed that rotary-wing experience may provide a slight advantage in acquiring basic aviation skills in eVTOL aircraft; however, fewer benefits were notable with increasing levels of automation.

Evaluating Pilot Performance Using Simulator Data

Airspeed Data

In this section, we examine participant performance between the two platforms for airspeed (in knots) during takeoffs, enroute navigation, and approaches and landings across the three wing-borne legs for the first and fourth repetition of the profile (see *Figure 15*). The target airspeed during enroute navigation was a constant 100 knots.

Semi-Automated



Highly Automated

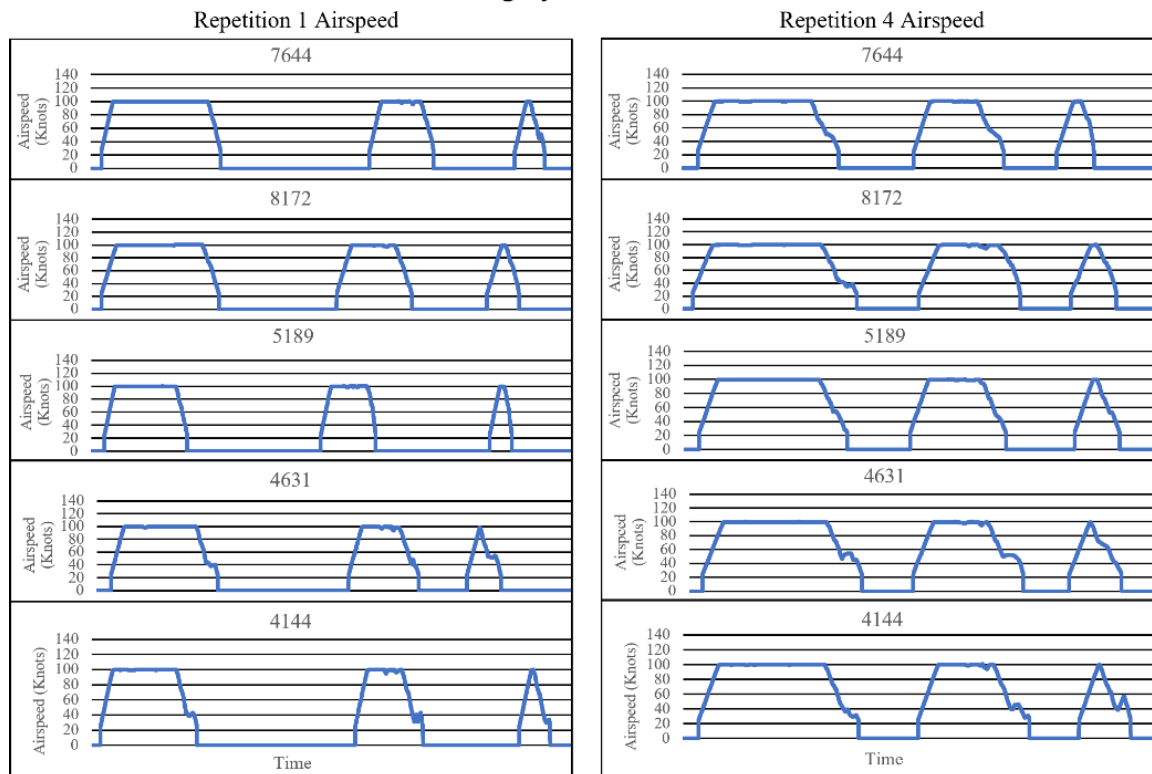


Figure 23 Airspeed Performance by Participant

Takeoffs

In general, airspeed performance was better in the highly-automated aircraft than in the semi-automated aircraft. On all takeoffs, including in the first repetition, all five pilots of the highly-automated platform were able to maintain consistent rates of acceleration to reach the target airspeed within 1 knot. While more variable than in the highly-automated platform, participants in the semi-automated platform showed highly consistent rates of acceleration during takeoffs in both the first and fourth repetition of the profile, demonstrating that even without high levels of automation, participants were able to quickly learn how to control acceleration during takeoff. However, there was a greater amount of variability in reaching the target airspeed by the end of takeoff. Exceeding or failing to reach the target airspeed by a significant margin was more frequent during the first repetition of the flight profile than during the fourth repetition, especially during the second takeoff; two participants (IDs 2404 and 6820) exceeded the target speed by 17 knots and one participant (0357) did so by an unsafe margin of 24 knots. The second takeoff included transitioning to wing-borne flight while flying over an obstacle, requiring pilots in a lower-drag aircraft to accelerate quickly. Participants likely needed more repetitions of the flight profile to become accustomed to the acceleration required.

Overall, all participants met conventional standards of proficiency in the rate of acceleration during takeoffs despite different levels of automation between the two platforms. Performance visibly differed in the participants' abilities to reach the target airspeed by the end of takeoff. In the highly-automated aircraft, airspeed is controlled by the human first setting and then activating a desired speed; the machine controls the execution of achieving and maintaining that speed. In contrast, airspeed in the semi-automated platform is controlled by constant minor adjustments made by the human

Enroute Navigation

In the highly-automated platform, extremely high levels of proficiency were seen for maintaining the target airspeed during enroute navigation. In fact, almost no deviations in airspeed were visible during most of the enroute navigation except some rapid but minor increases and decreases in speed during the steep turn around Roosevelt Island. In the first repetition, the most drastic of these deviations were still minor at only 7 knots (ID 4631), and most deviations were less than approximately 5 knots (proficient). For the fourth repetition, these very small deviations were still present but were reduced. In the highly-automated platform, airspeed is machine-controlled. To consistently maintain a given airspeed, the machine must make constant adjustments to accommodate the complex relationship between pitch, roll, and bank angle. Steep turns, such as this one, would therefore require more complex and rapid calculations to maintain the target airspeed. While machine performance was not perfect in maintaining 100 knots during this turn, the deviations were minute and are only of note because of the small level of variability seen for this platform.

For the semi-automated platform, overall, airspeed was much more variable during enroute navigation than it was for the highly-automated platform. Because participants frequently exceeded or failed to reach their target airspeed before leveling off in the semi-automated platform, large corrections were often required. However, after correcting the target, participants were typically able to maintain their airspeed within 5 knots of the target using many rapid but

small corrections to the controls. Major or unsafe increases or decreases of greater than 10 knots were seen only occasionally, and these were usually during periods of high task saturation (e.g., during turns) in both the first and fourth repetitions of the profile. For example, in participant 2404's first repetition of the flight profile, their airspeed approached 120 knots during the left-hand turn in the first leg, 85 knots while passing the Lincoln Memorial during the second leg, and had a significant decrease in airspeed to 72 knots before starting their approach to the White House during the third leg. By the fourth repetition, their airspeed was more consistent at around 100 knots, but they continued to show deviations from their target airspeed during the same points in the first leg, with an unsafe deviation at the second leg of the profile. Participant 6820 also had an unsafe deviation while passing the Lincoln Memorial in the second leg of the first and fourth repetitions, decreasing to 83 knots in both.

Overall, an examination of airspeed during enroute navigation revealed that participants showed high proficiency levels in their airspeed for both platforms. With the exceptions of corrections for exceeding or failing to reach the target airspeed in the semi-automated platform, most deviations were within 5 knots of the target. While this performance would be considered proficient, it was achieved with frequent, small changes in airspeed, suggesting a higher degree of pilot workload.

Approaches and Landings

Airspeed during approaches and landings was less variable for the highly-automated platform, as participants utilized a highly-automated landing function that is not available in the semi-automated platform. However, both platforms exhibit a "shelf" where airspeed stabilized or even briefly increased before decreasing during the transition from wing-borne to vertical flight. While the pattern looks similar between platforms, the root cause was slightly different. In the highly-automated platform, the pilot activates a setting to begin the approach, and the machine controls the rate of deceleration. If this setting is activated at the perfect moment, the aircraft will arrive at the landing zone without the need for additional human input. However, participants were instructed to activate the descent early to avoid reaching the landing site with excessive airspeed or altitude, causing a potentially hazardous condition. This instruction resulted in participants needing to provide additional inputs to airspeed and pitch (which also affects airspeed) to mitigate the deceleration rate (or in some cases, to actually accelerate).

Participants were instructed to provide 5 to 15 seconds of input as their airspeed approached approximately 30 to 50 knots. Examination of the control inputs revealed that participants were adjusting both the airspeed control and pitch control to increase speed during landings; however, some preferred more aggressive increases in airspeed than others (e.g., participant 4144). Interestingly, this pattern is slightly more prevalent during the fourth repetition (i.e., 8 of the 15 landings across all participants) of the profile than in the first (i.e., 7 of the 15 landings), suggesting that participants had a stronger preference to increase airspeed to reach the target destination rather than to delay activating the machine-controlled deceleration. This result suggests that participants relied more heavily on manual control over airspeed during landings rather than the automation features of the platform—a result that may be attributed to either personal pilot preferences or the type of training they received.

In contrast, the pattern in the semi-automated platform data was driven by a shift in how to control the vehicle that occurs during the approach and landing phase. As the aircraft makes its

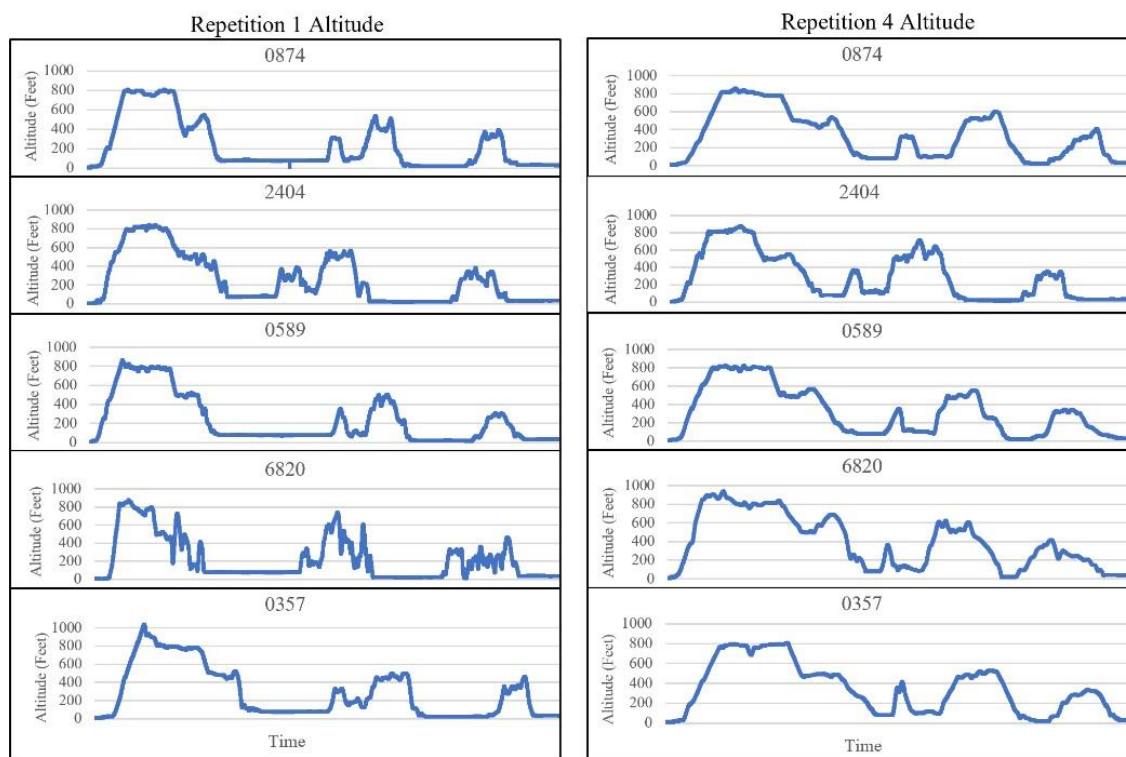
approach, it must transition from wing-borne flight, in which controls are similar to those in an airplane, to hovering, in which controls are similar to those in a helicopter. While wing-borne, the pilot controls airspeed controlled by adjusting the power; however, once the aircraft has transitioned into hovering, airspeed is controlled mainly by manipulating the aircraft attitude. Thus, to successfully command a consistent rate of deceleration, the pilot must make a mental shift to recognize that inputs to attitude will have a different effect on an aircraft now in hover while control inputs used for wing-borne airspeed will no longer have an effect. Participants frequently made this mental shift too late during the approach, which resulted in losing too much speed prior to reaching the landing site, as well as sometimes losing speed entirely while hovering before reaching the landing site. Consequently, participants were forced to increase speed again after the transition to hovering. For example, for participant 0357 (**Figure 15**), note the near-vertical line during the approach of the first two legs of the first repetition where the participants rate of deceleration was too rapid and eventually comes to a complete stop in a hover and must then increase speed again to reach the landing site. Notably, while many participants in the semi-automated platform showed improved control of speed during approaches and landings, this pattern of needing to accelerate during the approach was still present in the fourth repetition of the profile (i.e., present in 11 of 15 approaches in the first repetition and 9 in the fourth).

Altogether, results suggest that approaches and landings are an aspect of eVTOL flight, where airspeed performance is more variable compared to other phases of flight, regardless of the level of automation. While increasing speed during the approach in the highly-automated platform was not an incorrect strategy, a more consistent deceleration could have been achieved if the participants had relied more heavily on the machine-controlled features. In contrast, increases in speed during the approach for the semi-automated aircraft reflected difficulty making a mental shift in how to operate the aircraft as it transitioned between wing-borne flight and hovering, suggesting additional training will be required.

Altitude Data

In this section, we examine performance between the two platforms on altitude (in feet) during takeoffs, enroute navigation, and approaches and landings across the three wing-borne legs for the first and fourth repetition of the profile (see *Figure 16*). During the first leg, target altitudes included a 20-foot hover, a climb to 800 feet, and then a descent to 500 feet. In the second leg, target altitudes included a 300 foot-hover, a descent to 100 feet, and a climb to 500 feet. In the third leg, the target altitudes included a 50-foot hover and a climb to 300 feet.

Semi-Automated



Highly Automated

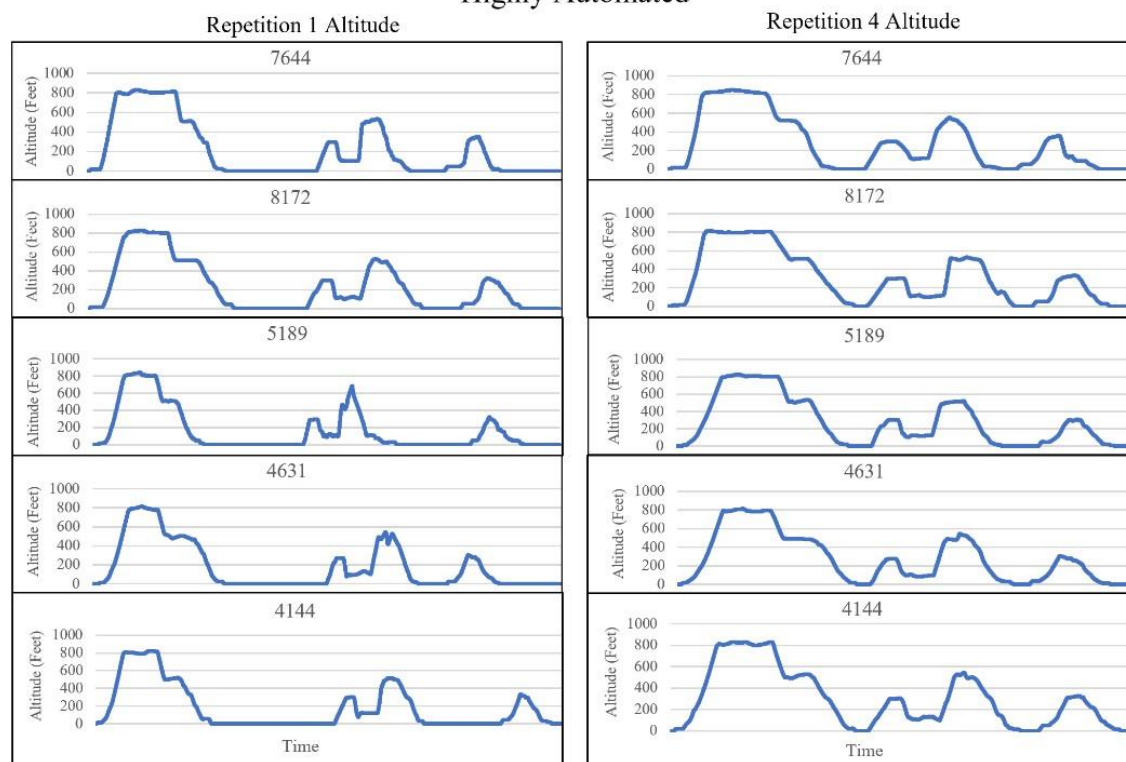


Figure 24 Altitude Performance by Participant

Takeoffs

Altitude performance was much less variable in the highly-automated platform than in the semi-automated platform during takeoffs. The participants in the highly-automated aircraft were able to achieve consistent climb rates during takeoff and showed almost no visible deviations in reaching the target altitude even during the first repetition of the profile. When participants of the highly-automated platform did exceed their target altitude, it was rarely by more than 20 feet, and by the fourth repetition of the profile, all five participants were able to meet their target altitudes within a few feet by the end of the climb.

Participants operating the semi-automated platform also exhibited a high level of proficiency in maintaining consistent climb rates during takeoffs, even during the first repetition of the flight profile. Climb rates were most variable during the final takeoff of the first repetition of the profile, where drops in altitude of up to 25 feet often occurred during the transition between hovering and wing-borne flight. By the final repetition, changes in climb rate were typically brief periods where the climb rate would slow with very few cases (e.g., ID 2404, first takeoff) where altitude was actually lost. With respect to reaching the target altitude, during the first repetition of the profile, participants showed proficient performance relative to conventional standards, typically reaching within 100 feet of their target altitudes by the end of takeoff. Only one major deviation of more than 200 feet from the target altitudes was seen during the first repetition of the profile (ID 0357; first takeoff) and only one minor deviation of greater than 100 feet was seen during the fourth repetition (ID 6820; final takeoff).

These differences in altitude performance between the two platforms during takeoff are likely related to how altitude is controlled. In the highly-automated platform, altitude is controlled by setting the climb angle without also having to make adjustments to correct for speed; input is the same regardless of whether the aircraft is hovering or in wing-borne flight leading to a more consistent climb rate, even during the transition between modes of flight. In contrast, the semi-automated platform requires two different control inputs for altitude between hovering (power) and wing-borne flight (pitch). Furthermore, power and pitch controls require continuous minor adjustments. Together, this switch in controls input and the continuous need for adjustments may reduce the ease with which participants can control climb rates and reach a target altitude compared to those in the highly-automated platform.

Enroute Navigation

In line with the findings for command of altitude during takeoffs, participants in the highly-automated platform were better able to achieve consistent climb and descent rates and to reach and maintain target altitudes than participants in the semi-automated platforms both on the first and fourth repetition of the flight profile.

Looking first at climbs and descents at higher altitudes (i.e., those that terminated above 100 ft) during enroute navigation, participants in both platforms showed low variability in their climb and descent rates (i.e., descending from 800 feet to 500 feet during the first leg and climbing from 100 to 500 feet while turning in the second leg), even during the first repetition of the profile. With respect to reaching the target altitude, during the first repetition of the profile, participants of the highly-automated platform demonstrated highly proficient performance, shifting to altitudes within approximately 20 feet of their target. In the semi-automated platform, performance reaching

the target altitude was more variable, ranging from near perfect (e.g., ID 0589) to unsafe deviations of over 300 feet below the target altitude (i.e., ID 6820). By the fourth repetition of the profile, all participants on the semi-automated platform were able to reach within 100 feet of their target altitude during the descent during the first leg, but a high level of variability remained in participants' abilities to climb to the target altitude in the second leg with one participant showing a major deviation of over 200 feet above their target. The variability in the second leg may be due to the climb taking place at the same time participants are performing a steep turn to follow the Potomac River.

Next, looking at maintaining higher altitudes, after correcting for exceeding the target altitude during takeoffs, participants in the semi-automated platform were typically within 100 feet of the target altitude during straight and level flight at high altitudes during the first repetition of the flight profile, improving to within 50 feet during the fourth repetition. In general, altitude performance in the semi-automated platform improved between the first and fourth repetitions of the flight profile; however, participants still showed room for improvement, especially during turns. During the fourth repetition of the flight profile, during the first turn prior to the I-295 bridge, one participant's (ID 0357) altitude fell by more than 100 feet, and during the steep turn around Roosevelt Island in the second leg, two participant's (ID 0874 and 2404) altitude raised by more than 100 feet, one participant (ID 2404) almost raising to 200. In contrast, participants of the highly-automated platform were typically able to maintain altitude control with no visible deviations during straight and level flight and turns at high altitudes even during the first repetition of the flight profile. These participants showed very few deviations from their target altitude, and when they did, it was rarely more than 50 feet.

Overall, an examination of altitude during enroute navigation revealed that participants in both platforms were able to achieve a high level of proficiency at changing and maintaining altitude. While performance was high across the two platforms, performance on the semi-automated platform was more variable, showing more and slightly larger deviations from the target altitude. This is because altitude during wing-borne flight is controlled by making continuous inputs to the attitude of the aircraft in the semi-automated platform (similar to conventional airplanes). Small adjustments to the pitch are also necessary in the highly-automated platform, but are needed less frequently, leading to less frequent minor shifts in altitude. Participants in both platforms showed improvements in performance by the fourth repetition of the profile.

Approaches and Landings

Participants in the highly-automated flight platform showed more consistent and controlled rates of descent during approaches and landings than participants in the semi-automated platform. In comparison, participants in the semi-automated platform had more difficulty with their approaches and landings. This is especially seen during the first repetition of the profile, where some participants showed a rapid (and in some cases near-vertical) descent sometimes accompanied by an increase in altitude prior to landing. One participant (ID 6820) had what would be considered an unsafe deviation of more than 300 feet prior to their first landing. However, by the fourth repetition of the profile, participants had more prolonged and controlled descents. The only exceptions were that four participants (IDs 0874, 2404, 0589, 6820) showed smaller increases in altitude of approximately 20 feet prior to landing in the first leg, and two participants showed noticeable stair stepping during the descent (ID 0589, leg 2).

This pattern of results in the semi-automated platform again related to the mental shift that pilots must make in how their inputs affect flight during the transition from wing-borne to hovering. While wing-borne, altitude is controlled primarily by adjusting the aircraft's pitch; however, once the aircraft has transitioned into hovering, altitude is controlled by manipulating power with a different control. The pilot must actively monitor when this transition happens and switch which controls are being used to maintain a consistent rate of descent. Furthermore, this simulator did not display peripheral vision below the torso of the participant, making it more difficult to recognize the sink leading to late responses.

Overall, examination of altitude during approaches and landings demonstrated that the higher levels of automation led to relatively more consistent and controlled rates of descent. For the semi-automated platform, approaches and landings posed more of a challenge. Similar to the results for airspeed during approaches and landings, most of these difficulties stemmed from a shift in how inputs control the descent during the transition from wing-borne to hovering.

Participant Impressions of Performance and Training Effectiveness

When exploring the results of the subjective experience questions, a total of thirteen themes emerged (see *Figure 17* below). The following sections present the main results of each question included in the analysis with the associated tables.



Figure 25 Participants Impression Word Cloud

When examining parts of the mission that participants found to be easier than expected by platform, enroute ($n = 15$), transition from forward flight to hover ($n = 6$), and takeoff ($n = 5$) were most cited as easier than expected. In the highly-automated platform, hover ($n = 10$), controlling the aircraft ($n = 9$), and takeoff ($n = 5$) were easier than expected (see *Table 15*). When examining results of factors that were easier than expected by pilot types, ab initio pilots felt that the takeoff was easier than expected ($n = 9$), whereas rated pilots felt that hover ($n = 10$) and enroute navigation ($n = 12$) was easier than expected.

Table 15 Parts of Flying the Mission that were Easier than Expected

Platform	Pilot Type	Takeoff	Hover	Enroute	Transition	Using Controls	Other
Semi-Automated	Ab Initio	4	1	3	4	0	6
	Rated	1	3	12	2	1	3
Highly Automated	Ab Initio	5	3	0	1	4	1
	Rated	0	7	0	1	5	3

When examining participants' responses to their impression of the level of difficulty for the mission, in the semi-automated platform there was a nearly-even divide between participants who responded that the mission difficulty was low, medium, or high ($n = 11$, $n = 10$, $n = 13$; respectively). However, in the highly-automated platform, most found the difficulty to be low ($n = 15$), with only one participant finding the difficulty high (see *Table 16*). When examining this by pilot type, a similar trend was found for ab initio pilots with difficulty being almost evenly spaced across low and medium but not high ($n = 11$, $n = 10$, $n = 5$; respectively). When examining the impression of difficulty for rated pilots, overall, experienced pilots found difficulty to be low ($n = 15$).

Table 16 Impression of the Mission Difficulty

Platform Type	Pilot Type	Low Difficulty	Medium Difficulty	High Difficulty	Response Unclear
Semi-Automated	Ab initio	5	2	9	2
	Rated	6	8	4	1
Highly Automated	Ab initio	6	5	0	0
	Rated	9	2	1	3

When we asked participants what skills they felt could be improved on with greater applied effort (see *Table 17*), participants in both platforms overwhelmingly felt that landing would improve with greater effort (semi-automated $n = 19$, highly-automated $n = 12$). In the semi-automated platform, participants also felt that hover/taxi ($n = 9$) could improve. When looking only at those in the highly-automated platform, the second most common skill was approach ($n = 7$). Additionally, only those in the highly-automated platform cited banking ($n = 4$). When examining the data by pilot type, landing continued to be the skill that both ab initio pilots and rated pilots felt could greatly improve. This was followed by hover/taxi by rated pilots ($n = 10$).

Table 17 Skills Participants Felt they could Improve with Greater Effort

Platform	Pilot Type	Hover	Transition	Approach	Landing	Altitude Control	Banking	All Skills	Other
Semi-Automated	Ab initio	2	2	2	11	2	0	2	5
	Rated	7	1	2	8	1	0	4	3
Highly Automated	Ab initio	0	0	4	6	4	3	1	5
	Rated	3	1	3	6	0	1	1	4

When examining the results of the question related to which parts of flying the mission were more difficult than expected (see *Table 18*), participants identified landing as the most difficult in both

the semi-automated ($n = 20$) and highly-automated platforms ($n = 9$). In the semi-automated platform, hover/taxi ($n = 12$) was also commonly cited, followed by approach ($n = 7$) and transition ($n = 5$). In the highly-automated platform, approach ($n = 8$) and banking ($n = 5$) were also commonly cited. When examining by pilot type, landing was identified the most, followed by approach for both ab initio pilots ($n = 15$, $n = 4$) and rated pilots ($n = 14$, $n = 11$).

Table 18 Parts of the Mission More Difficult than Expected

Platform	Pilot Type	Hover	Transition	Approach	Landing	Altitude Control	Bank	Thrust	Yaw	Other
Semi-Automated	Ab initio	5	3	2	11	3	0	0	0	2
	Rated	7	2	5	9	1	0	2	0	1
Highly Automated	Ab initio	0	0	2	4	2	4	0	0	3
	Rated	1	1	6	5	0	1	0	2	4

When examining participants' responses about when they felt they had the most control of the aircraft, both those in the semi-automated platform ($n = 20$) and highly-automated platform ($n = 8$) identified enroute navigation (see *Table 19*). Participants in the semi-automated platform also noted takeoff ($n = 5$). When examining by pilot type, rated pilots identified hover/taxi ($n = 8$), while ab initio pilots did not.

Table 19 Moments Participants Had the Most Control

	Pilot Type	Take off	Hover	Enroute	Climb	Other	Response Unclear
Semi-Automated	Ab initio	2	0	8	2	1	3
	Rated	3	2	12	0	2	2
Highly Automated	Ab initio	2	0	3	1	3	6
	Rated	1	6	5	1	1	2

When examining participants responses about when they felt they had the least control of the aircraft (see *Table 20*), both those in the semi-automated platform ($n = 15$) and highly-automated platform ($n = 10$) identified landing. Those in the semi-automated platform also commonly identified hover/taxi ($n = 7$). Participants in the highly-automated platform also cited banking ($n = 4$). When examining the question by pilot type, rated pilots identified the transition from forward flight to hover ($n = 8$) as a moment where they felt they had least control, whereas ab initio pilots did not.

Table 20 Moments Participants Had Least Control

Platform Type	Pilot Type	Hover	Transition	Approach	Landing	Bank	Other	Response Unclear
	Ab initio	3	0	2	8	0	4	3

Semi-Automated	Rated	4	6	2	6	0	1	2
	Ab initio	0	0	2	2	2	4	6
Highly Automated	Rated	0	2	4	3	2	3	2

While the semi-automated eVTOL platform included some automation features, its controls were relatively similar to conventional fixed- and rotary-wing aircraft. In contrast, the highly-automated eVTOL platform included a greater variety of automation features, which we predicted would aid ab initio pilots in performing more similarly to rated pilots and to improve performance across both groups in general. Our results confirmed this prediction.

For hover maneuvers in the highly-automated platform, both groups followed a curvilinear learning trajectory showing slowing rates of improvement with each repetition of the flight profile, eventually resulting in a plateau. However, the plateaus in rated pilots may reflect performance approaching ceiling levels of 4.0 (i.e., proficient) during the third repetition of the profile and, in ab initio pilots, by reaching just under a rating of 4.0 during the fourth repetition. Thus, both groups were able to reach proficient levels of performance in hovering by the end of the fourth repetition of the profile. For both takeoff and enroute navigation maneuvers, ab initio pilots had different learning trajectories than rated pilots. However, rated pilots again approached ceiling levels of performance before the fourth repetition of the profile, which may have artificially produced a curvilinear trajectory for enroute navigation maneuvers and prevented analysis entirely for takeoff maneuvers, limiting our ability to compare true learning trajectories between rated and ab initio pilots. Again, because they started at a lower baseline level of performance, ab initio pilots would have required additional training to reach the same level of performance as rated pilots. However, the learning trajectories seen here suggest that the amount of additional training required would be relatively minimal.

For both takeoffs and enroute navigation, ab initio pilots would need approximately one additional repetition of the flight profile (i.e., three takeoffs or enroute navigation maneuvers).

Discussion

In a highly automated eVTOL simulator, participants performed significantly better than in an augmented system. The degree of automation has a positive impact on performance scores with greater automation increasing participants scores.

The second research question explored if there were significant BPR predictors of performance. An analysis of the combined devices yielded weak models. However, individual analysis found significant predictors for the highly-automated platform although the models were not strong. Significant BPR predictors and strong models were found for semi-automated platform.

Performance of Participants in Simulated Flight Operations

The current work examined the learning trajectories of ab initio and experienced pilots while they learned how to fly one of two simulated eVTOL platforms: one that was highly-automated and

one that was semi-automated. The first analysis investigated the time experienced pilots would need to become proficient in hovering, takeoff, enroute navigation, and approach and landing maneuvers under ideal conditions. Results revealed higher levels of baseline performance for participants in the highly-automated platform than in the semi-automated platform across all four maneuvers. Higher levels of automation led to improvements in performance, regardless of the maneuver type. For hover maneuvers, both groups followed the same linear learning trajectory, suggesting that learning progressed at the same rate irrespective of the levels of automation between the two platforms. For takeoff maneuvers, all participants in the highly-automated platform reached ceiling levels by the third repetition of the profile, whereas participants in the semi-automated platform followed a linear learning trajectory. For enroute navigation maneuvers, learning followed a quadratic trajectory that differed between the two groups, which suggested that participants in the highly-automated platform made smaller gains with each repetition of the profile than participants in the semi-automated platform. Finally, for approach and landing maneuvers, results revealed that participants followed the same learning trajectories between the two platforms, again suggesting no effect of automation on the rate of learning. Results were consistent with increased automation, leading to overall higher and more consistent levels of performance, but did not increase the rate at which learning occurred. In the case of hovering, approach and landing maneuvers, the rate of learning was identical between the two platforms, whereas for enroute navigation, pilots received less benefit with each repetition of the profile. Although we could not complete growth curve analyses for takeoff maneuvers in the highly-automated platform, these results suggest that automated takeoff features allowed for easy mastery of this maneuver.

Overall, the findings of the study indicate that under ideal conditions, participants would need a total of 1.5 to 3 hours of repeating the flight profile to reach proficient performance across the various types of maneuvers in the highly-automated platform and between 2 and 4 hours to reach proficient performance on the semi-automated platform. These findings provide guidance on how much time to allot in a curriculum for various aspects of eVTOL flight given a particular level of automation. Increased levels of autonomy also decreased the variability of performance, leading to more consistent outcomes. Although they are not directly comparable to the times found in **Table 1**, these results suggest that gaining proficient stick and rudder skills may take notably less time in eVTOLs than it would in conventional rotary- or fixed-wing aircraft

Learning Trajectories of Pilots and Ab Initio Participants

The second analysis compared the learning trajectories of experienced pilots with ab initio pilots in each platform to identify areas where particular attention may be warranted in training programs for inexperienced pilots. Results were consistent with rated pilots yielding higher baseline performance across all maneuvers in both platforms compared to ab initio pilots. However, the highly-automated eVTOL platform yielded smaller differences in performance between ab initio pilots and rated pilots. These results were expected given that greater amounts of experience typically lead to better performance even in a new context, and the higher-automation levels would be expected to aid ab initio pilots as less task load would be required. In the semi-automated platform, both pilot types showed a linear learning trajectory that did not differ for hover and takeoff maneuvers. Although ab initio pilots started at a lower baseline level of

proficiency, meaning more training time would be needed compared to rated pilots, learning advanced at a similar pace between the two groups. Extrapolating from the given learning trajectories, ab initio pilots would only need two additional repetitions of the flight profile (i.e., four hover maneuvers) to catch up to the starting levels of rated pilots on hover maneuvers and an additional three repetitions (i.e., six takeoff maneuvers) to catch up on takeoffs.

Unlike hover and takeoff maneuvers, a curvilinear learning trajectory was found for enroute navigation, approaches, and landings in the semi-automated platform. Ab initio pilots showed more difficulty with these maneuvers compared to the rated pilots in the semi-automated platform, although these two maneuvers also posed challenges for rated pilots as well. The curvilinear learning trajectories for enroute navigation and for approach and landing suggest that participants' performance increased by a smaller amount after every repetition of the flight profile until performance reached a plateau. For takeoff enroute maneuvers, rated pilots approached a rating of 4.0 (i.e., proficient) before leveling off, whereas ab initio pilots approached a rating of 3.0 (i.e., minor deviations). The effect was even more pronounced for approach and landings where rated pilots plateaued just above a rating of 3.0 (i.e., minor deviations) and ab initio pilots plateaued just above a rating of 2.0 (i.e., major deviations). Recall that IPs provided less instructional guidance with each repetition of the flight profile and provided only ATC commands during the final repetition. Thus, this plateau in performance does not indicate that participants would not have eventually reached a high level of proficiency. Instead, it suggests that participants needed additional, active instruction to continue to improve. As such, enroute navigation, and especially approach and landing maneuvers are an area for more targeted intervention during training for eVTOL aircraft with lower levels of automation. This is particularly true for ab initio pilots, who, due to their lower baseline levels of performance, leveled off at nearly one full rating level below rated pilots.

When examining the highly-automated platform, hover maneuvers for both groups followed a curvilinear learning trajectory showing slowing rates of improvement with each repetition of the flight profile, eventually resulting in a plateau. However, the plateaus in rated pilots may reflect performance approaching ceiling levels of 4.0 (i.e., proficient) during the third repetition of the profile and, in ab initio pilots, by reaching just under a rating of 4.0 during the fourth repetition. Thus, both groups were able to reach proficient levels of performance in hovering by the end of the fourth repetition of the profile. For both takeoff and enroute navigation maneuvers, ab initio pilots had different learning trajectories than rated pilots. Rated pilots again approached ceiling levels of performance before the fourth repetition of the profile, which may have artificially produced a curvilinear trajectory for enroute navigation maneuvers and prevented analysis entirely for takeoff maneuvers, limiting our ability to compare true learning trajectories between rated and ab initio pilots. Although ab initio pilots would have required additional training to reach the same level of performance as rated pilots, the learning trajectories suggest that the amount of additional training required would be relatively minimal. For both takeoffs and enroute navigation, ab initio pilots would need approximately one additional repetition of the flight profile (i.e., three takeoffs or enroute navigation maneuvers). It is important to state that the value for takeoffs is an estimate, as growth curve analyses could not be completed. Finally, for approach and landing maneuvers in the highly-automated platform, both ab initio and rated pilots followed the same linear learning trajectory, suggesting that both groups learned at the same rate. To reach a similar level of performance to that of rated pilots, the ab initio pilots would have needed

an additional three repetitions of the flight profile (i.e., nine approaches and landings). As such, approaches and landings proved to be the most challenging aspect of eVTOL flight for ab initio pilots to master in the highly-automated platform—and, in fact, in both platforms. In contrast to the approach and landings in the semi-automated platform, ab initio pilots in the highly-automated platform were still progressing towards a rating of 4.0 (i.e., proficient) at the end of the fourth repetition of the flight profile, whereas participants in the semi-automated platform had reached a plateau. These findings suggest that a lower level of active intervention would be needed for participants across both platforms to reach a rating of proficient in the highly-automated platform than in the semi-automated platform.

Overall, the results of the study revealed four key findings that have relevance for the development of eVTOL curricula for ab initio pilots: First, especially with higher levels of automation, ab initio pilots were able to achieve relatively high levels of performance (i.e., only minor deviations). This suggests that new eVTOL pilots do not necessarily need to be experienced in operating conventional fixed- or rotary-wing aircraft prior to beginning training. Second, as expected, ab initio pilots yielded lower baseline levels of performance across all maneuvers, regardless of the level of automation. Ab initio pilots will need more training than rated pilots to reach similar levels of performance. Third, greater levels of automation reduced the gap in learning rates between ab initio and rated pilots. Even for approach and landing—the most challenging maneuver for both groups—ab initio pilots showed a linear progression toward reaching a rating of proficient, despite decreasing levels of instructional input from the IP. Finally, results show that future training programs designed for ab initio pilots (and to some extent, even rated pilots) should place particular emphasis on approaches and landings in both types of platforms but especially for eVTOL platforms that feature lower levels of automation. Likely due to the transition from wing-borne to rotary flight, approach and landing maneuvers proved to be the most challenging aspect of eVTOL flight and will likely require the greatest amounts of active instruction in curricula designed for ab initio pilots.

Evaluating Pilot Performance Using Simulator Data

The third analysis examined the performance of a subset of experienced pilots in both aircraft platforms in airspeed and altitude across takeoffs, enroute navigation, and approaches and landings. In general, airspeed performance was better in the highly-automated aircraft than in the semi-automated aircraft. On all takeoffs, including in the first repetition, all five pilots of the highly-automated platform were able to maintain consistent rates of acceleration to reach the target airspeed within 1 knot. While more variable than in the highly-automated platform, participants in the semi-automated platform showed highly consistent rates of acceleration during takeoffs in both the first and fourth repetition of the profile, demonstrating that even without high levels of automation, participants were able to quickly learn how to control acceleration during takeoff. However, there was a greater amount of variability in reaching the target airspeed by the end of takeoff. Exceeding or failing to reach the target airspeed by a major margin was more frequent during the first repetition of the flight profile than during the fourth repetition.

Participants likely needed more repetitions of the flight profile to become accustomed to the acceleration required. Overall, all participants met conventional standards of proficiency in the rate of acceleration during takeoffs despite different levels of automation between the two

platforms. Performance visibly differed in the participants' abilities to reach the target airspeed by the end of takeoff. In the highly-automated aircraft, airspeed is controlled by the human first setting and then activating a desired speed; the machine controls the actual execution of achieving and maintaining that speed. In contrast, airspeed in the semi-automated platform is controlled by constant minor adjustments made by the human.

When examining the task of maintaining target airspeed enroute, the highly-automated platform showed extremely high levels of proficiency. In fact, almost no deviations in airspeed were visible during most of the enroute navigation except some rapid but minor increases and decreases in speed during the steep turn around Roosevelt Island. In the first repetition, the most drastic of these deviations were still minor around 5 knots. For the fourth repetition, these very small deviations were still present but reduced. In the highly-automated platform, airspeed is machine-controlled. To consistently maintain a given airspeed, the machine must make constant adjustments to accommodate the complex relationship between pitch, roll, and bank angle. Steep turns, such as this one, would therefore require more complex and rapid calculations to maintain the target airspeed. While machine performance was not perfect in maintaining 100 knots during this turn, the deviations were minute and are only of note because of the small level of variability seen for this platform. For the semi-automated platform overall, airspeed was much more variable during enroute navigation than it was for the highly-automated platform. Because participants frequently exceeded or failed to reach their target airspeed before leveling off in the semi-automated platform, large corrections were often required. However, after correcting to the target, participants were typically able to maintain their airspeed within 5 knots of the target using many rapid but small corrections to the controls. Major or unsafe increases or decreases of greater than 10 knots were seen only occasionally, and these were usually during periods of high task saturation (e.g., during turns) in both the first and fourth repetitions of the profile.

Overall, examination of airspeed during enroute navigation revealed that participants showed high levels of proficiency in their airspeed for both platforms. With the exceptions of corrections for either exceeding or failing to reach the target airspeed in the semi-automated platform, most deviations were within 5 knots of the target. While this performance would be considered proficient, it was achieved with frequent, small changes in airspeed, suggesting a higher degree of pilot workload.

Airspeed during approaches and landings was less variable for the highly-automated platform, as participants utilized a highly-automated landing function that is not available in the semi-automated platform. However, both platforms exhibit a "shelf" where airspeed stabilized or even briefly increased prior to then decreasing during the transition from wing-borne to vertical flight. While the pattern looks similar between platforms, the root cause was slightly different. In the highly-automated platform, the pilot activates a setting to begin the approach and the machine controls the rate of deceleration. If this setting is activated at the perfect moment, the aircraft will arrive at the landing zone without the need for additional human input. However, participants were instructed to activate the descent early to avoid reaching the landing site with excessive airspeed or altitude, causing a potentially hazardous condition. This instruction resulted in participants needing to provide additional inputs to airspeed and pitch (which also affects airspeed) to mitigate the rate of deceleration (or in some cases to actually accelerate). Participants were instructed to provide 5 to 15 seconds of input as their airspeed approached

approximately 30 to 50 knots. Examination of the control inputs revealed that participants were making adjustments to both the airspeed control and pitch control to increase speed during landings; however, some preferred more aggressive increases in airspeed than others. Interestingly, this pattern is slightly more prevalent during the fourth repetition, suggesting that participants relied more heavily on manual control over airspeed during landings rather than use the automation features of the platform. This is a result that may be attributed to either personal pilot preferences or to the type of training they received. In contrast, the pattern in the semi-automated platform data was driven by a shift in how to control the vehicle that occurs during the approach and landing phase. As the aircraft makes its approach, it must transition from wing-borne flight, in which controls are similar to those in an airplane, to hovering, in which controls are similar to those in a helicopter. While wing-borne, airspeed is primarily controlled by adjusting the power; however, once the aircraft has transitioned into hovering, airspeed is primarily controlled by manipulating the aircraft attitude. Thus, to successfully command a consistent rate of deceleration, the pilot must make a mental shift to recognize that inputs to attitude will have a different effect on an aircraft now in hover while control inputs used for wing-borne airspeed will no longer have an effect. Participants frequently made this mental shift too late during the approach, which resulted in losing too much speed prior to reaching the landing site, sometimes losing speed entirely while hovering before reaching the landing site. Consequently, participants were forced to increase speed again after the transition to hovering. Notably, while many participants in the semi-automated platform showed improved control of speed during approaches and landings, this pattern of needing to accelerate during the approach was still present in the fourth repetition of the profile (i.e., present in 11 of 15 approaches in the first repetition and 9 in the fourth).

The results of altitude performance support lower variability in the highly-automated platform than in the semi-automated platform during takeoffs. The participants in the highly-automated aircraft were able to achieve consistent climb rates during takeoff and showed almost no visible deviations in reaching the target altitude even during the first repetition of the profile. When participants of the highly-automated platform did exceed their target altitude, it was rarely by more than 20 feet, and by the fourth repetition of the profile, all five participants were able to meet their target altitudes within a few feet by the end of the climb. Participants operating the semi-automated platform also exhibited a high level of proficiency in maintaining consistent climb rates during takeoffs, even during the first repetition of the flight profile. Climb rates were most variable during the final takeoff of the first repetition of the profile, where drops in altitude of up to 25 feet often occurred during the transition between hovering and wing-borne flight. By the final repetition, changes in climb rates were typically brief periods where the climb rate would slow with very few cases where altitude was actually lost. With respect to reaching the target altitude, participants showed proficient performance relative to conventional standards during the first repetition of the profile, typically reaching within 100 feet of their target altitudes by the end of takeoff. Only one major deviation (i.e., of more than 200 feet from the target altitude; ID 0357; first takeoff) was seen during the first repetition of the profile, and only one minor deviation of greater than 100 feet was seen during the fourth repetition (ID 6820; final takeoff). In line with the findings for command of altitude during takeoffs, participants in the highly-automated platform were better able to achieve consistent climb and descent rates as well as to reach and maintain target altitudes than participants in the semi-automated platforms both on

the first and fourth repetition of the flight profile. Looking first at climbs and descents at higher altitudes (i.e., those that terminated above 100 ft) during enroute navigation, participants in both platforms showed low variability in their climb and descent rates (i.e., descending from 800 feet to 500 feet during the first leg and climbing from 100 to 500 feet while turning in the second leg), even during the first repetition of the profile. With respect to reaching the target altitude, during the first repetition of the profile, participants of the highly-automated platform demonstrated highly-proficient performance, shifting to altitudes within approximately 20 feet of their target. In the semi-automated platform, performance reaching the target altitude was more variable, ranging from near-perfect (e.g., ID 0589) to unsafe deviations of over 300 feet below the target altitude (i.e., ID 6820). By the fourth repetition of the profile, all participants on the semi-automated platform were able to reach within 100 feet of their target altitude during the descent during the first leg, but a high level of variability remained in participants' abilities to climb to the target altitude in the second leg with one participant showing a major deviation of over 200 feet above their target. The variability in the second leg may be due to the climb taking place at the same time participants are performing a steep turn to follow the Potomac River. When examining maintaining higher altitudes, after correcting for exceeding the target altitude during takeoffs, participants in the semi-automated platform were typically within 100 feet of the target altitude during straight and level flight at high altitudes during the first repetition of the flight profile, and this improved to within 50 feet during the fourth repetition. In general, altitude performance in the semi-automated platform improved between the first and fourth repetitions of the flight profile; however, participants still showed room for improvement, especially during turns. During the fourth repetition of the flight profile, one participant's (ID 0357) altitude fell by more than 100 feet during the first turn prior to the I-295 bridge, and during the steep turn around Roosevelt Island in the second leg, two participant's (ID 0874 and 2404) altitude raised by more than 100 feet, with one participant (ID 2404) almost raising to 200. In contrast, participants of the highly-automated platform were typically able to maintain altitude control with no visible deviations during straight and level flight and turns at high altitudes even during the first repetition of the flight profile. These participants showed very few deviations from their target altitude, and when they did, it was rarely more than 50 feet.

Participants in the highly-automated flight platform showed more consistent and controlled rates of descent during approaches and landings than participants in the semi-automated platform. In comparison, participants in the semi-automated platform had more difficulty with their approaches and landings. Especially during the first repetition of the profile, some participants showed a rapid (and in some cases near-vertical) descent sometimes accompanied by an increase in altitude prior to landing. One participant (ID 6820) had what would be considered an unsafe deviation of more than 300 feet prior to their first landing. However, by the fourth repetition of the profile, participants had more prolonged and controlled descents. The only exceptions were that four participants (IDs 0874, 2404, 0589, 6820) showed smaller increases in altitude of approximately 20 feet prior to landing in the first leg, and two participants showed noticeable stair stepping during the descent (ID 0589, leg 2). This pattern of results in the semi-automated platform again related to the mental shift that pilots must make in how their inputs affect flight during the transition from wing-borne to hovering. While wing-borne, altitude is controlled primarily by adjusting the pitch of the aircraft; however, once the aircraft has transitioned into hovering, altitude is controlled by manipulating power with a different control. The pilot must actively

monitor when this transition happens and switch which controls are being used to maintain a consistent rate of descent. Furthermore, this simulator did not display peripheral vision below the torso of the participant, making it more difficult to recognize sink leading to late responses. Altogether, results related to airspeed suggest that approaches and landings are an aspect of eVTOL flight, where airspeed performance is more variable compared to other phases of flight, regardless of automation level. While increasing speed during the approach in the highly-automated platform was not an incorrect strategy, a more consistent deceleration could have been achieved if the participants had relied more heavily on the machine-controlled features. In contrast, increases in speed during the approach for the semi-automated aircraft reflected difficulty making a mental shift in how to operate the aircraft as it transitioned between wing-borne flight and hovering, suggesting additional training will be required. Results related to altitude point to higher levels of automation yielding relatively more consistent and controlled approaches and landings.

For the semi-automated platform, approaches and landings posed more of a challenge while enroute navigation in both platforms were able to achieve a high level of proficiency at changing and maintaining altitude. Similar to the results for airspeed during approaches and landings, most of these difficulties stemmed from a shift in how inputs control the descent during the transition from wing-borne to hovering. While performance was high across the two platforms, performance on the semi-automated platform was more variable, showing more and slightly larger deviations from the target altitude. This is because altitude during wing-borne flight is controlled by making continuous inputs to the attitude of the aircraft in the semi-automated platform (similar to conventional airplanes). However, participants in both platforms showed improvements in performance by the fourth repetition of the profile.

Participant Impressions of Performance and Training Effectiveness

The final analysis examined responses to the self-report questionnaire to further understand the results of the study qualitatively. The two platforms differed in how easily participants found enroute navigation and controls. First, in the semi-automated platform, rated pilots especially found enroute navigation to be easier than expected compared to those in the highly-automated platform, who did not mention enroute navigation. When comparing these results to the quantitative results for enroute navigation (*i.e.*, *Airspeed and Altitude Control* section), rated pilots in the semi-automated platform showed high levels of proficiency in their airspeed and altitude performance even though it required them to make small, frequent changes in airspeed and altitude control during enroute navigation. One possible explanation of these results is that rated pilots expected there to be a larger difference in aircraft handling for eVTOL aircraft, and although those in the semi-automated platform had fewer automation features available to them for this aspect of flight, the use of continuous inputs may have felt similar to those used in fixed-wing conventional aircraft. Second, with respect to controls, the semi-automated platform showed only one participant mentioned the ease of using the controls, whereas nine participants mentioned the ease of using controls in the highly-automated platform. This difference was expected as the increases in automated features reduce the amount of factors

the pilot must control. For example, to maintain altitude, the pilot simply sets a climb angle and does not need to make speed corrections, thereby lowering the task load and need to learn the finer details of performing this in the aircraft. In contrast, participants in the semi-automated aircraft must continuously monitor and adjust their power and pitch. Although doing so is similar to conventional aircraft, it is more complex than that of the highly-automated aircraft.

The participants' perception of mission difficulty differed between the two platforms. Difficulty in the semi-automated aircraft was more evenly distributed, whereas many more participants felt that the difficulty was low for the highly-automated aircraft. Perceived difficulty differed minimally between pilot type with no ab initio pilots finding the highly-automated platform to be high in difficulty, suggesting that higher levels of automation could lend support even for those with limited experience. Although most rated pilots found the platforms to be low in difficulty, many rated pilots in the semi-automated platform felt there was still a medium level of difficulty. Similar trends were found between the results related to the times participants had more difficulty than expected, felt they had the least control, and skills they felt they could improve on. Participants overwhelmingly cited approach and landings for these three questions, followed by hovering and transitions. These results mirror the results of other sub-studies in the larger study that showed some of the lowest performance on approach and landings, which are also historically the most difficult to teach in conventional aircraft as it is a high-workload phase of flight. With respect to platforms, those in the semi-automated platform cited approach and landings more than those in the highly-automated platform. One possible explanation for this result is that the maneuver presents a higher task load compared to the highly-automated platform at the beginning of the approach during the transition phase. More specifically, airspeed is primarily controlled by adjusting the power in wing-borne flight and primarily controlled by manipulating the aircraft attitude in hover. This shift in controls requires high recall and resulted in difficulty for participants as at times they lost too much or all speed prior to reaching the landing site. Although commonly cited, more participants in the semi-automated platform cited hovering as being more difficult than expected and felt they had the least control compared to those in the highly-automated platform. One possible reason may be the greater amounts of automation features for hovering in the highly-automated platform. Results of the other sub-studies also found higher baseline levels of performance were achieved for hovering in the highly-automated aircraft compared to the semi-automated platform. Furthermore, hovering was commonly cited by rated pilots in the highly-automated platform as a moment when they felt they had the most control (this discrepancy was also present in the semi-automated platform but much smaller). These findings suggest that automation support during hovering is beneficial in eVTOL aircraft. However, rated pilots noted that they felt their hovering would improve with more effort, especially in the semi-automated condition. One possible explanation is simply the pilots were aware of their difficulty and knew it was something that could improve. It was found that learning trajectories for hovering did not differ between the two groups (i.e., *Level of Experience* results section), and although rated pilots started at a higher level of proficiency, they grew in proficiency at a rate similar to that of the ab initio pilots. Possibly, rated pilots may have been more attune to their slower growth in proficiency between repetitions, while ab initio pilots may have felt that their gains in proficiency between repetitions was more positive compared to the other maneuvers.

Conclusion

This series of studies followed the basic performance resources and learning trajectories of more than 80 experienced and novice pilots as they learned to fly a simulated eVTOL platform with either a high or moderate amount of automation using expert ratings of performance, objective system-based data, and self-reports of experience. This research explored the following research objectives:

- RO1. Measure cognitive and psychomotor resource availability.
- RO2. Evaluate the performance of participants in simulated flight operations.
- RO3. Describe the learning trajectories of rated pilots and ab initio participants in eVTOLs
- RO4. Compare the performance of rotary-wing pilots to fixed-wing pilots in eVTOLs
- RO5. Evaluate pilot performance using simulator data outputs
- RO6. Describe participant impressions of performance and learnability.

We discovered some of the basic performance resources measured did predict performance, however this observation was dependent on the level of automation in the vehicle. A less automated vehicle required more cognitive and psychomotor capacity for pilots to be successful. Increasing levels of automation do influence human performance. Across all studies, flight performance tended to be better in the more highly-automated platform than in the semi-automated platform. Higher levels of automation placed less demand on the innate human performance resources.

Participants who flew the highly-automated platform, regardless of level of experience, tended to be rated as more proficient and showed less variability in their airspeed and altitude control. Whereas higher levels of automation did appear to improve performance.

Participants tended to have the most difficulty with hovering and approach and landing maneuvers, suggesting that future training programs should pay special attention to training on these types of maneuvers. Controls for both hovering and approach and landing maneuvers tend to be more dynamic, especially during the transition between wing-borne and hovering, thus requiring a greater level of multi-limb coordination and decision making than takeoff and enroute navigation. Importantly, participants in the highly-automated platform, who had access to greater levels of automation during these maneuvers, showed both higher perceived and actual control, again suggesting an advantage for automation features. It is worth noting that by the end of the approximate 2-hour training block, on average, experienced pilots were rated as having only minor deviations or better for their performance on hover and approach and landing maneuvers. Thus, while hover and approach and landing maneuvers were the most difficult for participants, learning was still relatively rapid.

Furthermore, experience played a factor in performance. Unsurprisingly, experienced pilots tended to have a higher baseline level of performance than ab initio pilots. Interestingly, ab initio pilots showed similar learning trajectories as experienced pilots for some maneuvers, especially for hovering and takeoffs. This suggests that ab initio pilots are able to learn how to perform these maneuvers at a similar rate as experienced pilots—they simply need more practice. On the other hand, ab initio pilots showed more difficulty with enroute navigation and approach and landings. Thus, training programs for ab initio pilots will likely need to have a stronger emphasis

on these types of maneuvers than training programs for experienced pilots. Altogether, the results of the line of studies are a starting point for illuminating the types of training requirements that will be necessary for training the first generation of eVTOL pilots. While our study did not address other types of training (e.g., airmanship, ground procedures, communication, emergency procedures), it provides an initial basis for curricula designers and policy makers in this emerging field to address future pilot's needs to become proficient at stick and rudder skills in eVTOL aircraft.

It is important to note that performance was relatively high in both platforms when compared to training times in conventional aircraft. This suggests that the presence of SVO in eVTOLs could reduce the amount of training necessary to learn basic stick and rudder skills. Increasing SVO also opens the window for a broader segment of the population to competently pilot these aircraft. Importantly, this does not mean that future eVTOL pilots will be less proficient pilots. Instead, it means a high level of proficiency will be easier and quicker to obtain.

Finally, A one-size fits all curriculum for eVTOLs would not be appropriate based on the different performance characteristics of the devices. The data clearly shows increased levels of SVO improves human performance, improves learning outcomes and reduces demands on basic performance resources. Training programs for eVTOLs should be tailored to SVO levels of the machine. The best way to ensure training programs produce competent aviators is to adopt outcome-based performance-driven airman certification standards that will pave the way for competency-based training systems.

Appendixes

- A. Permission to Conduct Research
- B. Informed Consent Letter
- C. Demographic Questionnaire
- D. Posttest
- E. Flight Profile
- F. SPOTLITE Evaluations
- G. Exit Interview
- H. Daily Schedule

Appendix A. Permission to Conduct Research



DEPARTMENT OF THE AIR FORCE AIR EDUCATION AND TRAINING COMMAND

MEMORANDUM FOR PRINCIPAL INVESTIGATOR

FROM: AETC/CD
1 F Street, Bldg 900
San Antonio, TX 78150

SUBJECT: Letter of Permission to Perform Research

1. Dr. Ellis has proposed conducting research by collecting data from Air Force members assigned to Air Education and Training Command. The data will be gathered from commercial aircraft simulator systems, a knowledge test, psychomotor skills assessments, and a participant questionnaire. The data he will be collecting and analyzing will not contain personally identifiable information. I have determined the proposed research is appropriate in context, is unique to my organization and participation would not impact mission readiness or performance.
2. I approve the use of data collected as described in the attached proposed research methodology with successful IRB review.
3. My point of contact for this matter is Dr. Steve Ellis, (228)-383-5529 or email stephen.ellis@afwerxpartner.com.

TULLOS.ANDREA.D. Digitally signed by
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Date: 2022.03.22 10:16:02 -05'00'

ANDREA D. TULLOS, Maj Gen, USAF
Deputy Commander

Attachments:
Research Methodology

cc:
AFRL 711 HPW/IR

Appendix B. Informed Consent Letter



**DEPARTMENT OF THE AIR FORCE
AIR EDUCATION AND TRAINING COMMAND**

9 March 2022

MEMORANDUM FOR RESEARCH PARTICIPANTS

FROM: AETC DET 62/CC
401 S. Frank Luke Dr.
San Antonio TX 78266

SUBJECT: Informed Consent to Participate in Research

1. Thank you for agreeing to participate in this study. Your participation will help future Air Force and civilian curriculum developers understand the learning profiles for eVTOL operations. Your participation will take approximately 5 hours to complete.
2. This study involves research into cognitive and psychomotor domains of learning. You will be given a series of tests to quantify psychomotor and cognitive agility. You will be given instruction in flying an electric vertical takeoff and landing eVTOL aircraft, and you will fly a structured flight profile in the eVTOL simulator. You will take a short test of your aviation knowledge both before you fly the simulator and after you complete your final flight of the day. At the end of the day, you will be asked to complete a questionnaire asking your opinion of your experiences in the study.
3. Potential risks of the research are minimal and are limited to tripping while entering and exiting the simulator trailer. Instructors and evaluators will be with you in the simulator throughout the events. If at any time you feel uncomfortable, let your instructor or evaluator know. If you have any questions, please contact Dr. Steve Ellis, stephen.ellis.8@us.af.mil.

FREDERICK M. HALEY III, Col, USAF
Commander

1 Ind.

Date _____

MEMORANDUM FOR AETC DET 62

I understand that participation in this experimental study is voluntary, that I will receive no compensation now or in the future for my participation. Furthermore, my refusal to participate will incur no penalty or loss of any benefit that I am otherwise entitled. I Understand my personally identifiable information will not be maintained in the records of this study.

Signature of Participant

cc:
Participant

Appendix C. COHRP Exemption Determination

CLASSIFICATION: UNCLASSIFIED

SUBJECT: Department of the Air Force (DAF) Component Office of Human Research Protections (COHRP) Exempt Determination Official (EDO) Review
 COHRP Protocol #: FSG20220013E
 Title: "Measuring the Effect of Electric Vertical Takeoff and Landing Aircraft Configurations on Pilot Performance," version received 22 April 2022
 Principal Investigator: Col Don Haley
 Submitter: Dr. Steve Ellis

References: (a) 32 CFR 219, Protection of Human Subjects, 19 January 2018
 (b) DoDI3216.02_AFI40-402_AFGM2020-01, Protection of Human Subjects and Adherence to Ethical Standards in Air Force Supported Research, 16 July 2021
 (c) DoDI 3216.02, Protection of Human Subjects and Adherence to Ethical Standards in DoD-Conducted and -Supported Research, 15 April 2020

1. DETERMINATION: I have reviewed the above activity as a DAF COHRP EDO. I have determined this activity is exempt research involving human subjects as defined in Reference (a), para 104(d)(3). The applicable exemption category is defined as follows: "Research involving benign behavioral interventions in conjunction with the collection of information from an adult subject through verbal or written responses (including data entry) or audiovisual recording if the subject prospectively agrees to the intervention and information collection and at least one of the following criteria is met: (A) The information obtained is recorded by the investigator in such a manner that the identity of the human subjects cannot readily be ascertained, directly or through identifiers linked to the subjects."
 1. Subjects will be healthy adults.
 2. The total research study time is five hours, plus a one hour mid-day break (six hours total).
 - i. The brief benign behavioral intervention portion of this study consist of four sortie simulator training flights totaling 110 minutes.
 - ii. The remainder of the study time will consist of data collection through various computer- and paper-based cognitive and psychomotor tests.
 3. The research all appears to be harmless, painless, not physically invasive, not likely to have a significant adverse lasting impact on the subjects, and the investigator has no reason to think the subjects will find the interventions offensive or embarrassing.
 4. The investigators will not maintain a key to the subjects' unique identifiers linking the codes to subject names.
2. IMPORTANT NOTES (MUST REVIEW):
 - a. Recruitment:
 - i. I understand the recruitment message was released in TMT before this EDO determination was issued. Recruitment is an important part of the informed consent process. In the future, recruitment for human research must not begin before EDO determinations are issued.
 - ii. Before recruiting any additional subjects, modify the last sentence of the recruitment message as follows: "Commanders and supervisors are prohibited from influencing

participation in research: they must not incentivize participation, nor punish non-participation."

- iii. Currently, this study only has component or command leadership approval to recruit Air Force members assigned to Air Education and Training Command. Before recruiting any other potential human subjects, first obtain approval from their command or Component as required by References (b) and (c). Please send any such approval to me for the file.
2. Consent: Though signed consent is not required for this exempt study, *informed consent* is still required. Ensure all researchers give subjects the informed consent (ICD Abbreviated V3_0, attached) and allow them time to read it to ensure they consent before beginning the research procedures.
3. Future Research: Col Haley has agreed to adopt the attached limited Human Research Protection Program Plan for the purposes of this study. If DET 62 expects to conduct human research in the future, please contact me to set up a more formal Human Research Protection Program plan to ensure required procedures are in place before the research begins.
3. CONTACT: Please contact me with any updates to this activity or questions about this determination.

Sincerely,
Jessica

Jessica Candia, JD, CIP
Acting Director
Component Office of Human Research Protections
Air Force Medical Readiness Agency
Defense Health Headquarters
7700 Arlington Blvd.
Falls Church, VA 22042

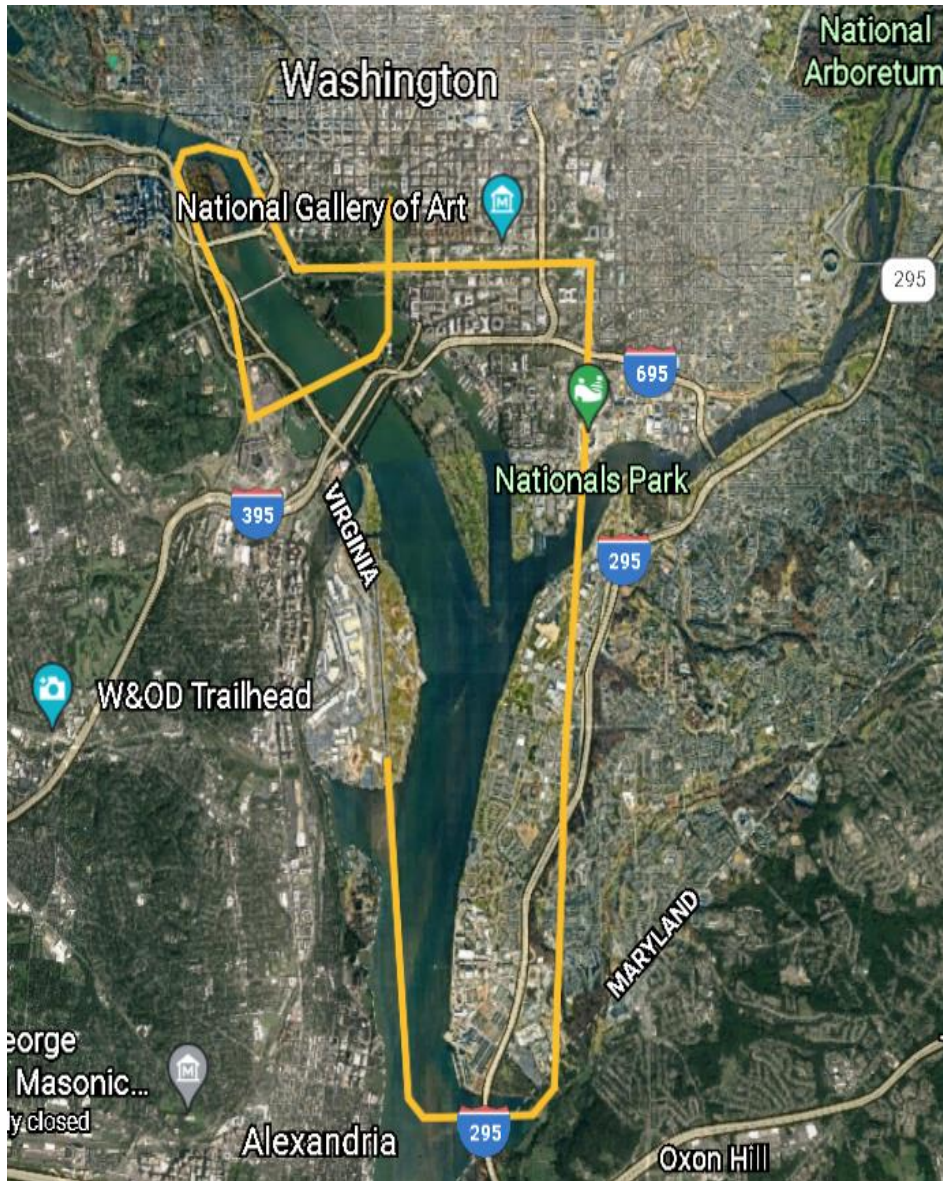
jessica.c.candia.civ@mail.mil
703-554-5144
CLASSIFICATION: UNCLASSIFIED

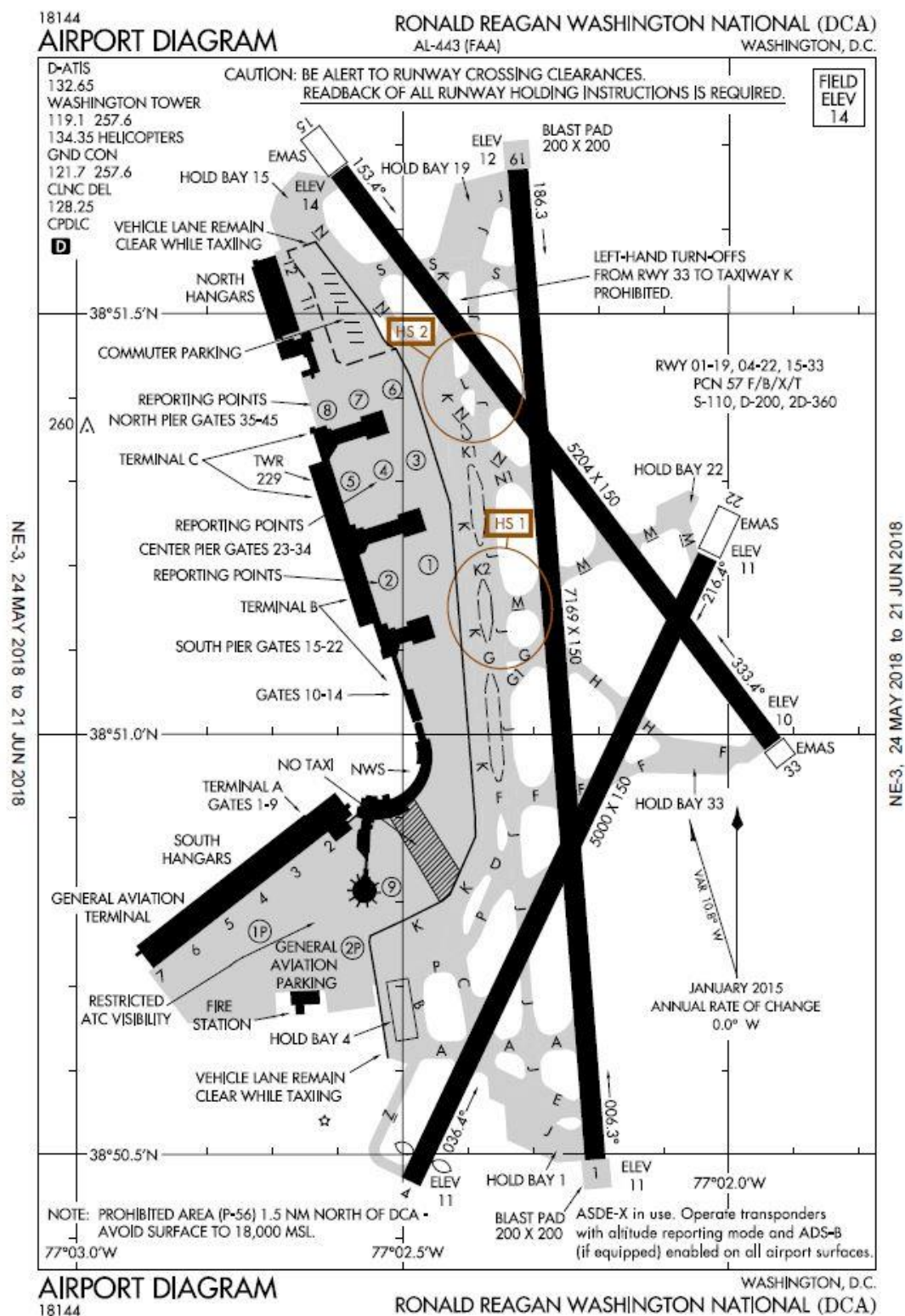
CLASSIFICATION: UNCLASSIFIED

Appendix D. Demographic Questionnaire

1. Please enter your assigned participant identifier
2. How many hours of piloting time do you have in the following aircraft: airplane, helicopter, drone?
3. How many hours do you spend playing video games in a typical week?
4. What is your age?
5. What is your gender?
6. What is your education level?

Appendix E. Flight Profile

Experimentation Flight Profile



MISSION SCENARIO

Time: Present day, Local time

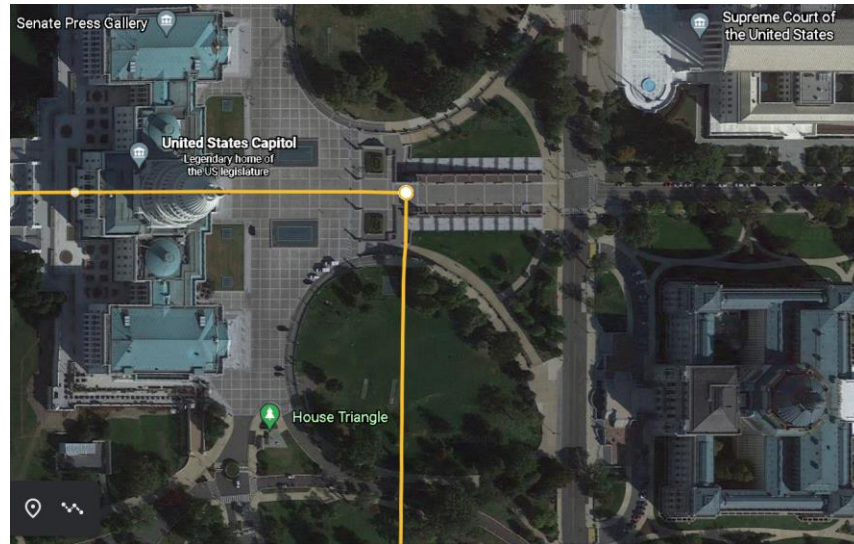
Weather: 00/000 SKC

Altimeter: Roll the altimeter to register 00 on the ground before each takeoff.

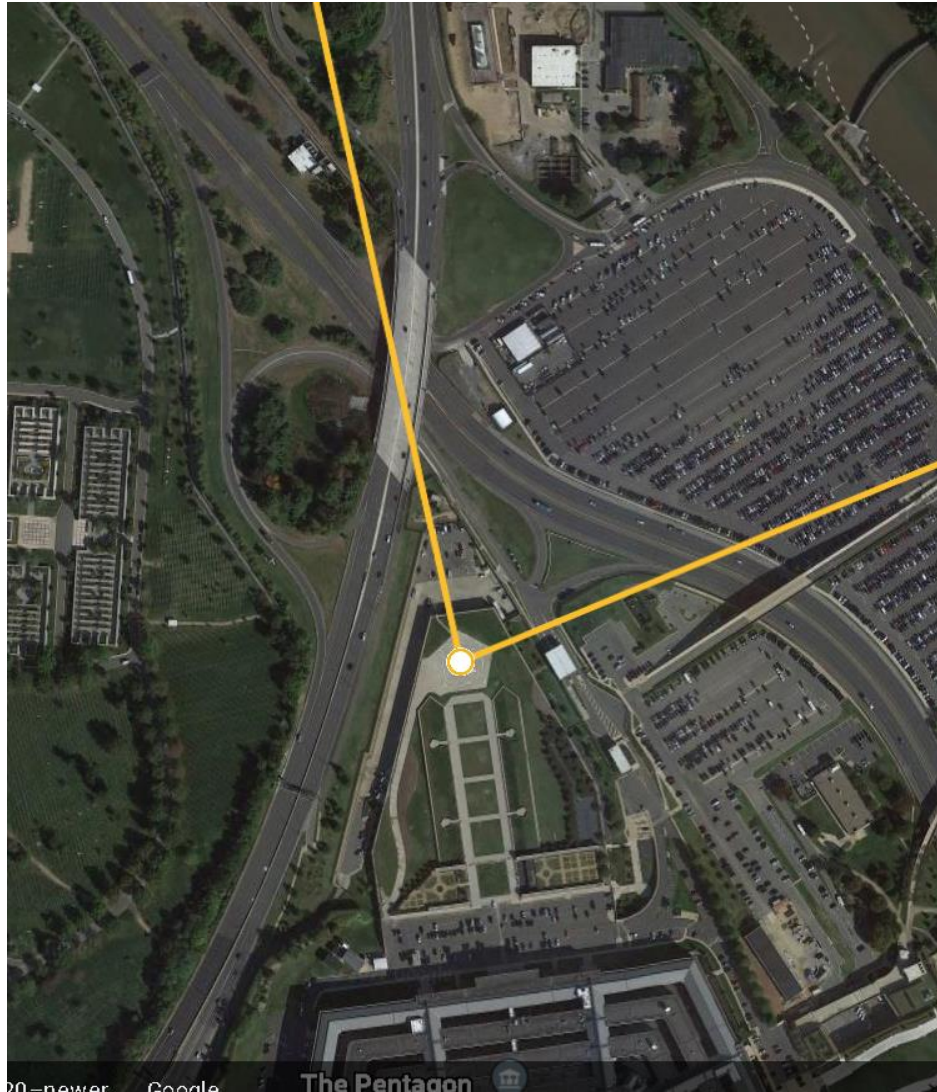
Starting Location: KDCA, Taxiway CHARLIE, holding short of Runway 04/22.

Use in-seat review to show the controls and indicators and to validate the participant has digested the information presented during ground academics.

- 1) ASTRO 01, ELEVATE AND MAINTAIN A 20 FOOT HOVER
 - a) *Have them stabilize before proceeding.*
- 2) ASTRO 01, TAXI RUNWAY 1-9 via CHARLIE, ALPHA, JULIET, ECHO.
 - a) *Provide progressive taxi instructions.*
 - b) *Have the participant taxi to the runway threshold markings and establish a hover. Once established, have the participant execute the box pattern exercise clockwise.*
 - c) *After finishing a full box pattern exercise, have the participant aligned on a 190 heading, and set the aircraft down on the ground.*
- 3) ASTRO 01, ELEVATE AND MAINTAIN A 20 FOOT HOVER
 - a) *Have them stabilize before proceeding.*
- 4) ASTRO 01 CLEARED TO TRANSITION, CLIMB AND MAINTAIN 800 FEET, HEADING 1-8-0, PROCEED AT 100 KNOTS
- 5) ASTRO 01, TURN LEFT HEADING 0-2-0, MAINTAIN 800 FEET, 100 KNOTS. REMAIN LEFT OF HWY 295.
 - a) *Inject when the north end of Highway 295 bridge is at 9 o'clock*
- 6) ASTRO 01 DESCEND AND MAINTAIN 500 FEET, PROCEED TO NATIONALS STADIUM AT 100 KNOTS
 - a) *Inject when abeam the departure end of Rwy 19*
 - b) *Mark the stadium with LASER*
- 7) ASTRO 01, CLEARED TO LAND AT THE CAPITOL BUILDING
 - a) *Inject over Nationals Stadium.*
 - b) *Mark the land point with a LASER.*



- 8) ASTRO 01 , ELEVATE AND MAINTAIN A 20 FOOT HOVER. TURN LEFT HEADING 280.
 - a) *Have them stabilize before proceeding.*
- 9) ASTRO 01, CLEARED TO TRANSITION, CLIMB OVER THE CAPITOL BUILDING LEFT OF THE DOME, THEN CONTINUE DOWN THE LEFT SIDE OF THE CAPITAL MALL AT 100 FEET AND 100 KNOTS.
- 10) ASTRO 01, TURN RIGHT. FOLLOW THE RIVER NORTH. CLIMB AND MAINTAIN 500 FEET, 100 KNOTS.
 - a) *inject passing Lincoln Memorial.*
- 11) ASTRO 01, TURN LEFT. FOLLOW THE RIVER AROUND THEODORE ROOSEVELT ISLAND. MAINTAIN YOUR AIRCRAFT OVER THE WATER.
 - a) *inject abeam the middle of Theodore Roosevelt Island.*
- 12) ASTRO 01, CLEARED TO LAND AT THE PENTAGON HELIPAD.
 - a) *Inject over Highway 66 bridge.*
 - b) *mark the landing point with a LASER*



13) ASTRO 01, ELEVATE AND MAINTAIN A 20 FOOT HOVER, TURN LEFT HEADING 0-8-0.

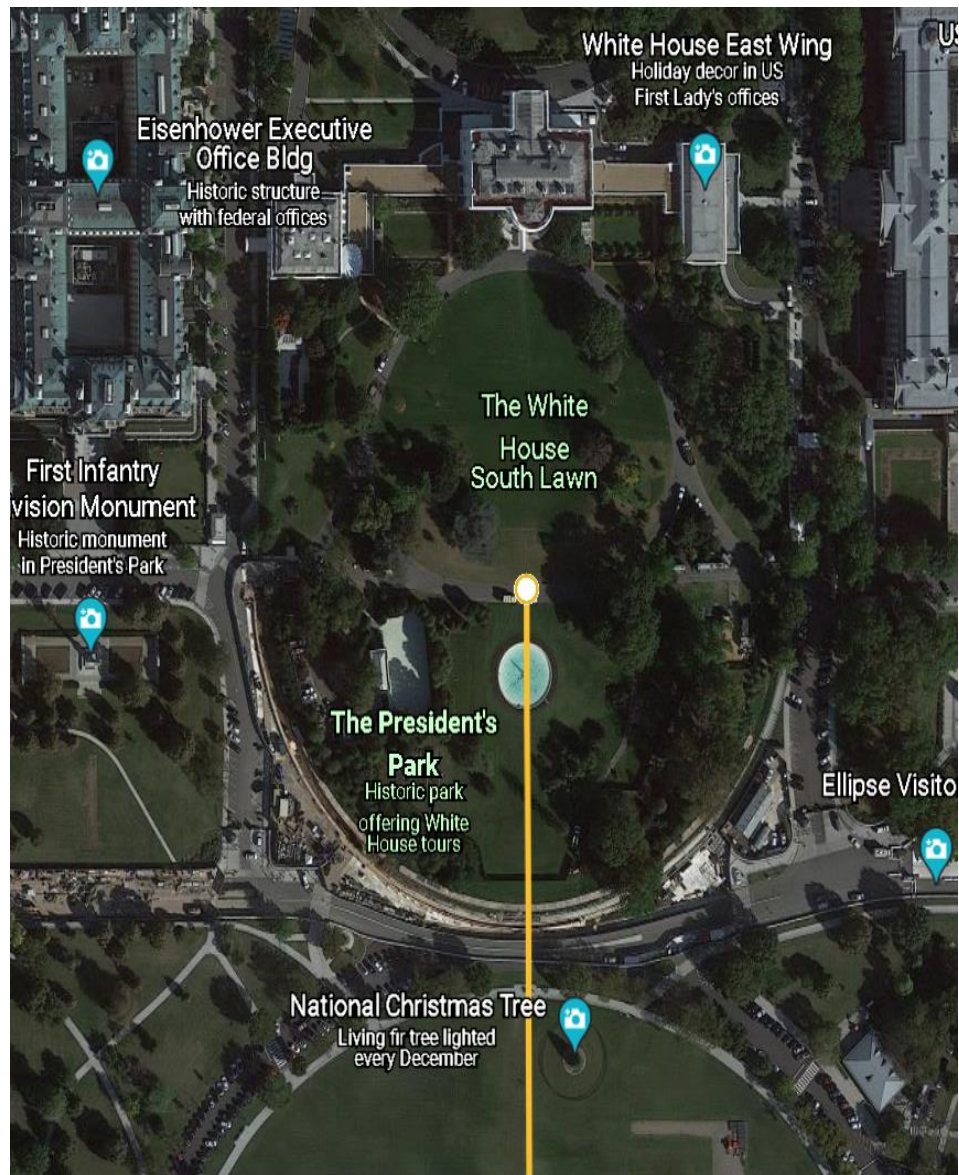
a) *Have them stabilize before proceeding.*

14) ASTRO 01 CLEARED TO TRANSITION, CLIMB AND MAINTAIN 300 FEET, HEADING 0-8-0, 100 KNOTS

15) ASTRO 01, TURN LEFT HEADING 0-1-0, CLEARED TO LAND AT THE WHITEHOUSE

a) *Inject when over Jefferson Memorial.*

b) *mark the landing point with a LASER.*



Appendix F. Instructor Pilot SPOTLITE Evaluations

Instructor Qualitative Evaluation Scale

1. Dangerous: (unable/unsafe) The member demonstrated an unacceptable level of safety performance or knowledge	2. Major Deviations: Capable of safely accomplishing task(s), but only with significant instruction (coaching) and/or deviation.	3. Minor Deviations: Capable of safely accomplishing task(s) with minor instruction and/or deviation. Minor deviations in altitude/position/ground track. Did not jeopardize safety, aircraft limitations, or maneuver effectiveness.	4. Proficient: Satisfactory performance within desired tolerances with no significant discrepancies. No additional training required.
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Instructor Input Level Scale

1. Full coaching on nearly all aspects of performance	2. Frequent coaching and corrective inputs	3. Infrequent corrective input , no coaching	4. No additional coaching or corrective input beyond script provided
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Self-report Scale (How well do you feel you did?)

1. Dangerous: (unable/unsafe) The member demonstrated an unacceptable level of safety performance or knowledge	2. Major Deviations: Capable of safely accomplishing task(s), but only with significant instruction (coaching) and/or deviation.	3. Minor Deviations: Capable of safely accomplishing task(s) with minor instruction and/or deviation. Minor deviations in altitude/position/ground track. Did not jeopardize safety, aircraft limitations, or maneuver effectiveness.	4. Proficient: Satisfactory performance within desired tolerances with no significant discrepancies. No additional training required.
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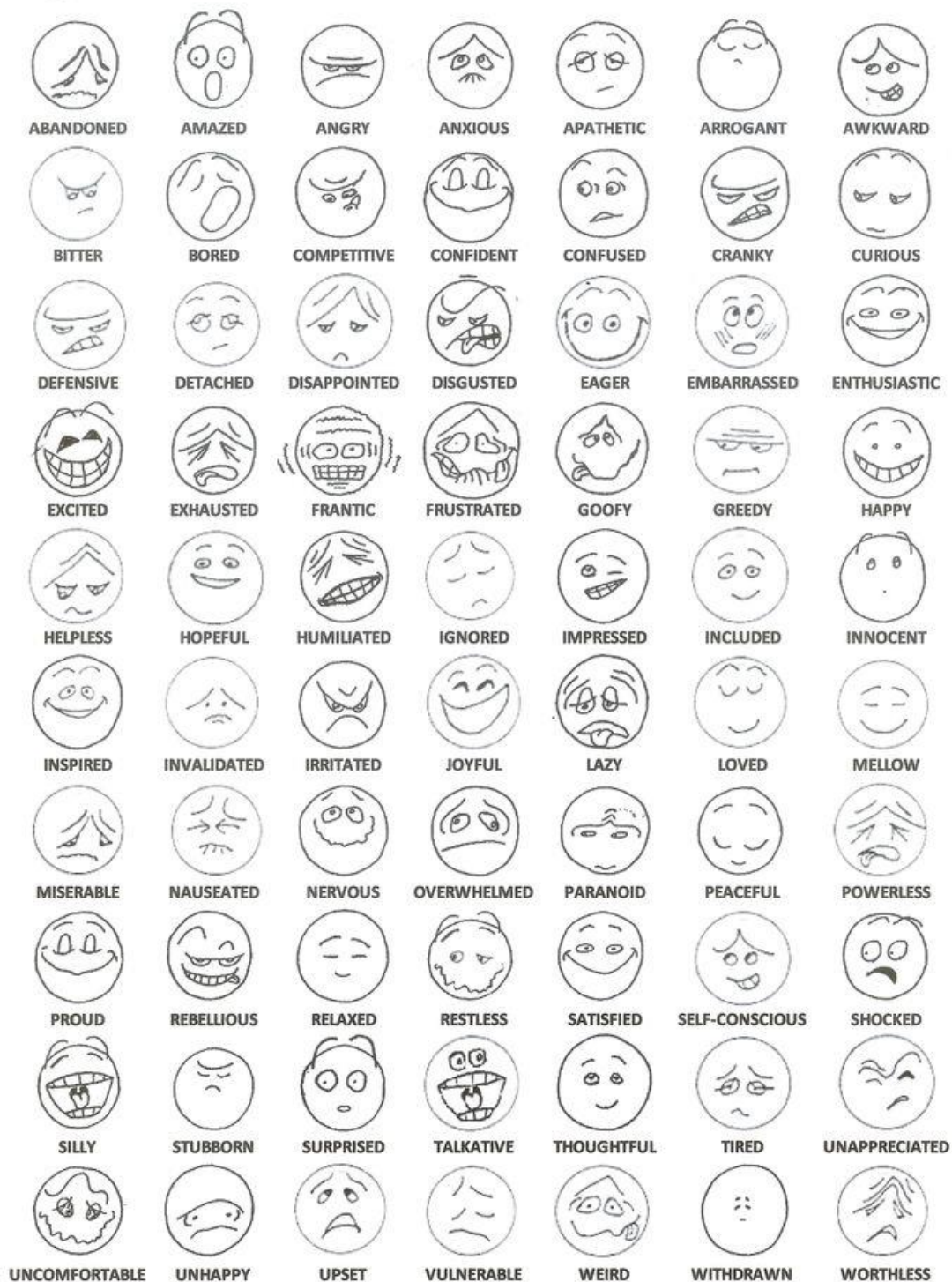
Comments

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Appendix G. Exit Survey

1. What parts of flying this mission were easier than you expected?
2. What parts of flying this mission were more difficult than you expected?
3. What skills did you feel you improved on with practice?
4. What skills do you feel you could have improved on with greater applied effort?
5. What is your impression of how easy/difficult it was to fly today's mission, and could you sustain this level of effort?
6. When did you feel you had the most control and least control of the aircraft?
7. What would you do differently to improve your performance?
8. What could we have done to improve your experience?

Right now I feel...



9. Pick one of the faces above that most closely matches how you are feeling now and explain why?

Appendix H. Daily Schedule

Approximate start time	Event
0830	Doors open, Welcome
0855	Orientation, Informed Consent, and intake log
0900	Psychomotor assessments
0930	Demographics
0950	Break
1000	Ground training video
1030	Orientation in simulator
1045	First flight with full coaching
1125	Break
1130	Second Flight, with coaching as required
1200	Lunch
1300	Third Flight, with coaching as required
1340	Break
1345	Fourth flight, without coaching
1415	Break
1430	Exit survey
1500	End of day

Appendix I. Maneuver-Based eVTOL Automations

A. Normal Takeoff and Climb						
The goal would be a consideration from the moment the aircraft leaves the ground until the aircraft has reached flying airspeed and is flying on the wing.						
Task	Highly Automated ^a			Semi-Automated ^b		
	<i>Automated</i>	<i>Augmented</i>	<i>Human</i>	<i>Automated</i>	<i>Augmented</i>	<i>Human</i>
1. Takeoff^c		X			X	X
1.1 Establish a stabilized hover ^c		X			X	X
1.1A Set an Altitude			X			X
1.1B Maintain Altitude		X				X
1.1C Control rate of climb		X				X
2. Climb		X				X
2.1 Turn to heading		X				X
2.2 Accelerate during Climb ^d	X					X
2.2A Maintain Airspeed	X					X

^aThe highly automated platform automates pitch and augments yaw and bank while in hover mode. In wingborne flight, pitch and yaw are automated and bank is augmented.

^bThe semi-automated platform augments yaw by automatically adjusting rotor RPM pitch and bank are entirely human controlled while in hover mode. In wingborne flight the human controls roll, pitch, and yaw.

^cThe semi-automated platform augments yaw by automatically adjusting rotor RPM pitch that impacts establishing a hover.

^dIn the highly automated platform acceleration is automated but the human can manually override.

B. Enroute Navigation						
The goal would be a consideration from the point the aircraft has reached flying airspeed and the lift rotors are turned off until the aircraft has begun its descent.						
Task	Highly Automated^a			Semi-Automated^b		
	<i>Automated</i>	<i>Augmented</i>	<i>Human</i>	<i>Automated</i>	<i>Augmented</i>	<i>Human</i>
1. Enroute		X				X
1.1 Changes in Altitude		X				X
1.2 Maintain Altitude ± 100 feet		X				X
2.1 Maintain heading ± 10 degrees		X				X
3.1 Changes in Airspeed		X				X
3.2 Maintain Airspeed	X					X

^aThe highly automated platform automates pitch and augments yaw and bank while in hover mode. In wingborne flight, pitch and yaw are automated and bank is augmented.

^bThe semi-automated platform augments yaw by automatically adjusting rotor RPM pitch and bank are entirely human controlled while in hover mode. In wingborne flight the human controls roll, pitch, and yaw.

C. Approach and Landing						
The goal would be a consideration from the moment an aircraft begins descent for landing until the aircraft has touched down.						
Task	Highly Automated^a			Semi-Automated^b		
	<i>Automated</i>	<i>Augmented</i>	<i>Human</i>	<i>Automated</i>	<i>Augmented</i>	<i>Human</i>
1. Approach to Land		X				X
1.1 Deceleration	X					X
1.2 Rate of Descent	X					X
2. Transition from forward flight to hover		X				X
2.1 Establish a stabilized hover ^c		X			X	X
3. Descent		X				X
4 Apply Brakes			X			X

^aThe highly automated platform automates pitch and augments yaw and bank while in hover mode. In wingborne flight, pitch and yaw are automated and bank is augmented.

^bThe semi-automated platform augments yaw by automatically adjusting rotor RPM pitch and bank are entirely human controlled while in hover mode. In wingborne flight the human controls roll, pitch, and yaw.

^cThe semi-automated platform augments yaw by automatically adjusting rotor RPM pitch that impacts establishing a hover

Appendix J. Maneuver-Based eVTOL Automations

Highly Automated Aircraft						
Thrust borne Flight						
Stabilized Hover		Automated	Augmented	Pilot		
	Roll	x				
	Pitch	x				
	Yaw	x				
	Heave	x				
	Sway	x				
	Surge	x				
Altitude Changes		Automated	Augmented	Pilot		
	Roll	x				
	Pitch	x				
	Yaw	x				
	Heave		x	→	Prop Pitch	Automated x
	Sway	x			Prop RPM	x
	Surge	x			Nacelle Angle	x
					Aileron	x
					Elevator	x
					Rudder	x
					Heave Command	
						x
Heading Changes		Automated	Augmented	Pilot		
	Roll	x				
	Pitch	x				
	Yaw		x		Prop Pitch	x
	Heave	x			Prop RPM	x
	Sway	x			Nacelle Angle	x
					Aileron	x
					Elevator	x
					Rudder	x
					Yaw Command	
						x
	Forward/Backwards		Automated	Augmented	Pilot	
Roll		x				
Pitch		x				
Yaw		x				
Heave		x				
Sway		x				
Surge			x	→	Prop Pitch	Automated x
					Prop RPM	x
					Nacelle Angle	x
					Aileron	x

				Elevator	x		
				Rudder	x		
				Surge			x
				Command			
Left/Right	Automated	Augmented	Pilot				
Roll	x						
Pitch	x						
Yaw	x						
Heave	x						
Sway		x	→	Prop Pitch	x		
Surge	x			Prop RPM	x		
				Nacelle Angle	x		
				Aileron	x		
				Elevator	x		
				Rudder	x		
				Sway			x
				Command			
Wingborne Flight							
Airspeed Changes	Automated	Augmented	Pilot				
Roll	x						
Pitch	x						
Yaw	x						
Heave	x						
Sway	x						
Surge		x	----->	Prop Pitch	x		
				Prop RPM	x		
				Nacelle Angle	x		
				Aileron	x		
				Elevator	x		
				Rudder	x		
				Airspeed			x
				Command			
Altitude Changes	Automated	Augmented	Pilot				
Roll	x						
Pitch	x						
Yaw	x						
Heave		x	→	Prop Pitch	x		
Sway	x			Prop RPM	x		
Surge	x			Nacelle Angle	x		
				Aileron	x		
				Elevator	x		
				Rudder	x		
				Heave			x
				Command			
Heading Changes	Automated	Augmented	Pilot				
Roll		x	→	Prop Pitch	x		
Pitch	x			Prop RPM	x		

Yaw	x	Nacelle Angle	x	
Heave	x	Aileron	x	
Sway	x	Elevator	x	
Surge	x	Rudder	x	
		Roll Command		x

Semi-Automated Aircraft				
Thrustborne Flight				
Stabilized Hover		Automated	Augmented	Pilot
	Roll	x		
	Pitch	x		
	Yaw			x
	Heave			x
	Sway			x
	Surge			x
Altitude Changes		Automated	Augmented	Pilot
	Roll	x		
	Pitch	x		
	Yaw			x
	Heave			x
	Sway			x
	Surge			x
Heading Changes		Automated	Augmented	Pilot
	Roll	x		
	Pitch	x		
	Yaw			x
	Heave			x
	Sway			x
	Surge			x
Forwards/Backwards		Automated	Augmented	Pilot
	Roll	x		
	Pitch			x
	Yaw			x
	Heave			x
	Sway			x

Left/Right	Surge			x
		Automated	Augmented	Pilot
	Roll			x
	Pitch	x		
	Yaw			x
	Heave			x
	Sway			x
	Surge			x
Wingborne Flight				
Airspeed Changes		Automated	Augmented	Pilot
	Roll			x
	Pitch			x
	Yaw	x		
	Heave			x
	Sway			x
	Surge			x
Altitude Changes		Automated	Augmented	Pilot
	Roll			x
	Pitch			x
	Yaw	x		
	Heave			x
	Sway			x
	Surge			x
Heading Changes		Automated	Augmented	Pilot
	Roll			x
	Pitch			x
	Yaw	x		
	Heave			x
	Sway			x
	Surge			x

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