# Automation and Augmentation on Human Performance in eVTOL Flight

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## ABSTRACT

Currently, electric vertical take-off and landing aircrafts (eVTOLs) are being built and tested with configurations varying from hover bikes to electric-ducted fans (Bacchini & Cestino, 2019). This new class of aircraft is drastically different from conventional aircraft and will require their own flight standards and curricula to train a new generation of pilots. Furthermore, the eVTOL market is highly competitive, where first-mover advantages can make or break a company and the pace of innovation is swift. It is, therefore, difficult for researchers to get access to eVTOL platforms to analyze the extent of augmentation to truly understand how the platform works as a human-machine team. This paper describes one of the first attempts to understand how varying levels of augmentation in eVTOLs influence aircraft performance. In a quasi-experimental design, simulated flight performance was examined across a total of 10 fixed-wing pilots in two simulated eVTOL aircraft, both of which are in the prototype phase and vary in the extent to which flight controls are automated and augmented. A simulated flight profile was designed involving a variety of eVTOL flight competencies, including takeoffs, dynamic enroute navigation, and approaches and landings. Participants repeated the same profile four times with decreasing levels of instructional feedback from an instructor pilot (IP). System-based data from the simulator were used to measure participants' control of airspeed and altitude to reveal differences in human performance between platforms during the first and fourth repetition of the profile. Results of the study provide the first step in understanding human (and machine) performance in an eVTOL context and may be used to inform eVTOL flight standards, develop training programs, and influence design decisions in the aircraft.

## ABOUT THE AUTHORS

**Dr. Samantha N. Emerson** is a Scientist at Aptima, Inc. with over a decade of experience designing and executing rigorous research on human learning, thought, and language. She has a multidisciplinary background that combines the theories, methods, and analytics of psychology, cognition, neuroscience, and psycholinguistics. Prior to joining Aptima, Dr. Emerson served as a Postdoctoral Research Scientist at Boys Town National Research Hospital where she examined the learning and productive use of visual and auditory patterns in the environment. She holds a PhD and MS in Cognitive Psychology from Georgia State University and a BS in Psychology from Middle Tennessee State University.

**Maria Chaparro Osman** is a Research Scientist Intern at Aptima, Inc., a Ph.D. candidate in Aviation Sciences with a focus in Human Factors in Florida Tech's College of Aeronautics, and a lead researcher at Florida Tech's ATLAS Lab. She received a B.S. in Technical Communication and New Media from the University of South Florida and an M.S. in Aviation Human Factors from Florida Tech. Her research interests include performer/learner engagement in complex monitoring tasks and for operational and training contexts, usability, and user experience.

**Dr. Cait Rizzardo** is a Scientist at Aptima, Inc. with experience in performance assessment, evaluating simulation-based training programs, spatial navigation research, and in developing testing protocols for research done in virtual environments. Currently, she supports several projects researching training effectiveness across a variety of audiences including pilots, maintainers, and ground and logistics operators for both the Air Force Research Laboratory (AFRL) Warfighter Interactions & Readiness Division and Air Education and Training Command (AETC). Dr. Rizzardo has assisted with and led projects

involving spatial knowledge acquisition, cross-cultural linguistic norms, display design and evaluation for after-action review and, prior to joining Aptima, Dr. Rizzardo conducted graduate research on spatial knowledge acquisition while using a redesigned GPS display, which resulted in an award-wining article in the *Journal of Experimental Psychology: Applied*. She also assisted in developing a spatial-acoustic navigation study with the AFRL Battlespace Acoustics Branch. Dr. Rizzardo holds a PhD and MS in Human Factors/Industrial and Organizational Psychology from Wright State University and a BA in Psychology from Hollins University.

**Kent C. Halverson** is a Principal Scientist and Senior Director of the Training, Learning, and Readiness Division at Aptima, Inc. He has research experience in performance measurement, organizational analysis, workflow modeling, training design and evaluation, survey development, social network analysis, and quantitative data analysis. Dr. Halverson manages a portfolio of research projects for a variety of DoD research agencies such as the Air Force Research Lab, across a variety of operational domains (e.g., military pilots, infantry soldiers, intelligence analysts), levels of analysis (e.g., individuals, teams, organizations), and research perspectives (e.g., cognitive, behavioral, process, system). Dr. Halverson has held faculty positions at the Air Force Academy and the Air Force Institute of Technology as the Director of the Graduate Engineering Management Program. He holds a PhD in Business Administration (Organizational Behavior) from the University of Florida, a MS in Civil/Structural Engineering from the University of Illinois, and a BS in Civil Engineering from the U.S. Air Force Academy.

**Steve Ellis** is a scholar-practitioner serving as a Learning Coordinator for the United States Air Force AFWERX Agility Prime program. He has over 30 years of experience as a technical training instructor, curriculum developer, training program evaluator, and training systems innovator. He researches how to improve efficiency and effectiveness in occupational skills training. He collaborated with colleagues to create and field instructor development workshops explaining student-centered instruction. He has a Ph.D. in Human Capital Development from the University of Southern Mississippi. He has published U.S. Air Force training policy, instructions, process guides, articles in performance improvement journals, and book chapters for student centered instruction.

**Lieutenant Colonel Andrew Anderson** is the Director of Operations, Detachment 62, Headquarters Air Education and Training Command. He currently supports AFWERX Agility Prime by accelerating the commercial and military adoption of electric vertical takeoff and land (eVTOL) aircraft through curriculum development and training. Lt. Col. Anderson has over 2900 hours in the C-17, MQ-1 and T-6 aircraft and over 600 hours of civilian flight experience. He was an instructor pilot in the MQ-1 and T-6 and worked as a civilian flight instructor prior to joining the Air Force. Lt. Col. Anderson is a 2005 graduate of the University of North Dakota and earned a Master of Aeronautical Science from Embry-Riddle Aeronautical University in 2015.

**Colonel Don "Stryker" Haley** is Commander, Detachment 62, Headquarters Air Education and Training Command. In his current role, he supports AFWERX Agility Prime by accelerating the commercial and military adoption of electric vertical takeoff and landing vehicle (eVTOL) technologies through curriculum development and training. An F-15E fighter pilot and former fighter squadron commander, he has over 3200 hours and 700 combat hours. He taught fighter lead-in training as a T-38 instructor at Euro-NATO Joint Jet Pilot training and was an F-15E evaluator and instructor pilot. Col. Haley is a 1999 graduate of Vanderbilt University and has three masters' degrees, including a fellowship in the Army School of Advanced Military Studies. A strategist and operational planner, he has led numerous planning efforts, including authoring operational plans for the defense of South Korea. During a three-year tenure at the Pentagon, he was the Chief of USAF joint wargaming and DARPA liaison. He developed numerous novel warfighting concepts, which directly drove future force design and capability development. Additionally, Stryker serves as a speaker & executive consultant for Afterburner, teaching companies how to accelerate performance by leveraging the techniques of elite military teams.

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## INTRODUCTION

Electric vertical take-off and landing (eVTOL) aircraft are set to revolutionize the transportation of passengers and cargo. Although vertical take-off and landing vehicles have been in existence for decades, many novel prototypes have been created in the last decade (Garrow, German, & Leonard, 2021; Mathur, Panesar, Kim, Atkins & Sarter, 2019) have greener, electric or hybrid propulsion, are generally smaller, and can be highly automated (Lombaerts, Kaneshige, & Feary, 2020). EVTOL aircraft will be able to navigate efficiently and safely in congested urban areas, while also being capable of supporting longer flights in suburban locations, referred to as Urban Air Mobility (UAM). Initial goals targeted for UAM include short distance operations within metropolitan areas but will expand to other operations rapidly (Garrow et al., 2021; Mathur et al., 2019).

One prominent benefit of many eVTOL aircraft is that they feature Simplified Vehicle Operations (SVO), wherein augmented and/or automated controls are combined with simplified display information to reduce pilot workload Increasing augmentation and automation within SVO can free the pilot from having to perform tasks easily accomplished by automated systems, such as controlling airspeed. This off-loading allows the pilot to focus on aspects of flight not easily carried out by automation, such as landing in difficult terrain (GAMA, 2019). Many eVTOL aircraft feature unified controls inspired by the F-35B, which decouples the axes (i.e., roll, pitch, yaw), ensuring that input on one axis does not affect the others (Thorsen, 2016; Lombaerts et al., 2020). The use of SVO as both a philosophy and as a standard in the UAM context will be a change for the aviation industry, likely requiring novel training requirements along with new regulations, as there are currently no existing regulatory frameworks that can support the technology or flight rules proposed for UAM (Vajda and Maris, 2021). Fortunately, existing levels of augmentation and automation have resulted in reduced training times for proficiency (Denham, 2016; Holden & Goel, 2016; Thorsen, 2016). This may indicate that it will take less time and fewer resources to train eVTOL pilots compared to training program demands for conventional aircraft.

GAMA (2019) suggested that highly automated systems will eventually reach a level of reliability that is equal to or even better than human performance. Future increases in the level of automation of these aircraft have the potential to decrease the amount of time necessary to train new pilots. As such, the SVO and the eVTOL industry could, in turn, have an impact on lowering training costs and mitigating the commercial pilot shortage, ongoing since 2009 (Holden & Goel, 2016; Federal Aviation Administration, 2019a). A key component of designing training for these aircraft will be understanding how varying levels of augmentation and automation affect learnability. As such, Air Education and Training Command (AETC) Detachment 62 conducted a study to compare the learnability of two simulated eVTOL aircraft with different levels of augmentation and automation.

### Platforms

Two simulated eVTOL platforms were evaluated: one designed for a semi-automated eVTOL and one for a highly automated eVTOL. Both aircraft had some augmentation, such as stability control, but large differences existed for

most features of flight (see Figure 1). 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; direction and speed were affected by manipulating the attitude (e.g., pitch, roll, and yaw axes) of the aircraft and altitude was controlled by 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; as an example, a change in attitude would affect the altitude of the aircraft while in hover. Further, it has no envelope protection (e.g., bank angle, rate of climb/descent).

In the highly automated eVTOL platform, while hovering, speed and altitude were controlled by human inputs on controls that were spring loaded to center. When a pilot 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. While in forward, wing-borne flight, rate of acceleration and deceleration was programmed and controlled by the machine. This machine control could be manipulated by the pilot to affect the rate at which the aircraft sped up or slowed down. Altitude was controlled by the pilot setting the desired pitch which the aircraft would hold when the controls were released. To turn, the aircraft had to be held in a bank and would return to a wings-level attitude when the controls were released. Envelope protections while wing-borne limited bank and pitch and prevent stalling.

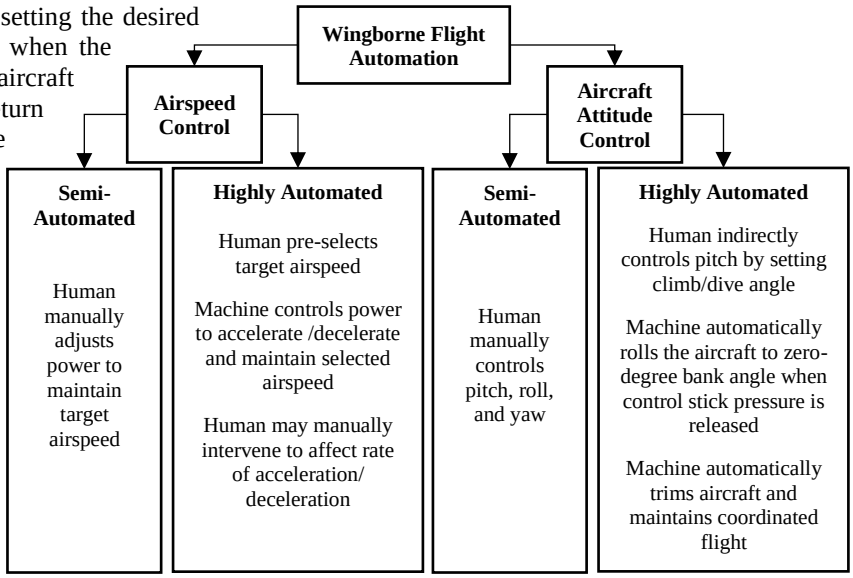



**Figure 1. Human-Machine Teaming in the Semi- and Highly Automated eVTOL Platforms**

## METHODS

### Participants

The sample for the study included 10 male volunteers (mean age = 45 years, *SD* = 9) at the USAF Joint Base in San Antonio. Participants were recruited for the study using snowball sampling. All 10 participants had fixed-wing flight experience, and no participants with other aircraft experiences were included (see Table 1). Participants in the semi-automated platform and in the highly automated platform had an average total number of 3534 flight hours (*SD* = 436) and 3772 flight hours (*SD* = 606), respectively. No compensation was provided for study participation.

**Table 1. Participants**

| Semi-Automated eVTOL | | | | Highly Automated eVTOL | | | |
|---|---|---|---|---|---|---|---|
| **Participant ID** | **Sex** | **Age** | **Total Flight Hours** | **Participant ID** | **Sex** | **Age** | **Total Flight Hours** |
| 0874 | Male | 37 | 3910 | 7644 | Male | 40 | 3450 |
| 2404 | Male | 58 | 3200 | 8172 | Male | 40 | 3463 |
| 0589 | Male | 41 | 3700 | 5189 | Male | 55 | 3114 |
| 6820 | Male | 47 | 3910 | 4631 | Male | 59 | 4475 |
| 0357 | Male | 34 | 2950 | 4144 | Male | 40 | 4360 |

### Procedures

Participants completed informed consent and a demographic questionnaire. They were then randomly assigned to the semi-automated aircraft or the highly automated aircraft in a quasi-experimental design. Participants viewed a training video that gave a brief description of the unique aspects of their assigned eVTOL aircraft, an overview of its controls,

and a preview of the full flight profile. The training video was created with the goal of covering 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 was simulated in the Washington D.C. area and included easily identifiable landmarks (Figure 2). It included three profile segments, or legs, that included wing-borne flight. Each leg was designed to cover 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. ATC commands and basic flight guidance were scripted; IPs attempted to follow the script as closely as possible but were allowed to deviate from the script when participant performance demanded additional or alternative input. During the first repetition of the flight profile, IPs gave additional, individualized input 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.

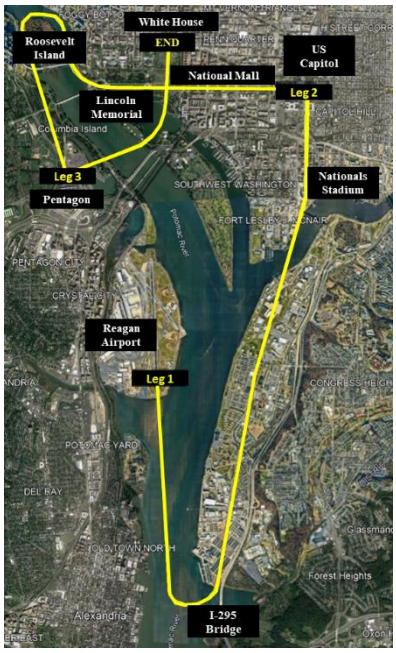



**Figure 2. Flight Profile**

## Data & Analysis

Systems-based data were captured continuously from the flight simulators; the simulators were built by different companies and therefore sampled data at different rates, 10 Hz (highly automated) and 95 Hz (semi-automated). This paper focuses on the wing-borne legs during each participant's first and fourth repetitions of the flight profile. 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, while data from the fourth repetition provided information on how much their performance improved after approximately two hours of experience flying in the simulator. Although data were collected along a variety of dimensions (e.g., pitch, bank, yaw, duration, human control inputs), the current paper focused on airspeed (in knots) and altitude (in feet) performance by plotting these two dimensions on line graphs.

Quality of flight performance was assessed by examining the variability of airspeed and altitude. For airspeed, performance during takeoffs was assessed by evaluating the rate of acceleration and the participants' ability to reach the target airspeed. During en route navigation, the variability of airspeed was assessed by the participants' ability to maintain a target airspeed. During approaches and landings, the variability of airspeed was assessed by the rate of deceleration. Based on conventional standards for airspeed adapted from the Practical Test Standards (Federal Aviation Administration, 1998, 2019b), deviations up to 5 knots from a target airspeed were considered proficient, between 5 and 10 knots were considered minor deviations, between 10 and 15 knots were major deviations, and deviations above 15 knots were considered unsafe. For altitude, performance during takeoffs was assessed by evaluating the climb rate and the participants' ability to reach the target altitude. For level flight during enroute navigation, the variability of altitude was assessed by the participants' ability to maintain a target altitude. For climbs and descents during en route navigation, the variability of altitude was assessed by climb/descent rates and the participants' ability to reach a target altitude. Finally, during approaches and landings, the variability of altitude was assessed by the descent rate. Based on conventional standards for altitude adapted from the Practical Test Standards (Federal Aviation Administration, 1998, 2019b), deviations up to 100 feet from a target altitude were considered proficient, between 100 and 200 feet were considered minor deviations, between 200 and 300 feet were major deviations, and deviations greater than 300 feet were considered unsafe. However, at lower altitudes, a narrower range of variations in altitude is allowable for safe flight.

# RESULTS & DISCUSSION

## Airspeed

In this section, we examine participant performance between the two platforms for airspeed (in knots) during takeoffs, en route navigation, and approaches and landings across the three wing-borne legs for the first and fourth repetition of the profile (see Figure 3). The target airspeed during enroute navigation was always 100 knots.

**Airspeed Performance: 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 major 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 a transition to wing-borne flight while flying over an obstacle, requiring pilots in a suddenly lower drag aircraft to accelerate in rapid succession. Participants likely needed more repetitions of the flight profile to become accustomed to the acceleration required.

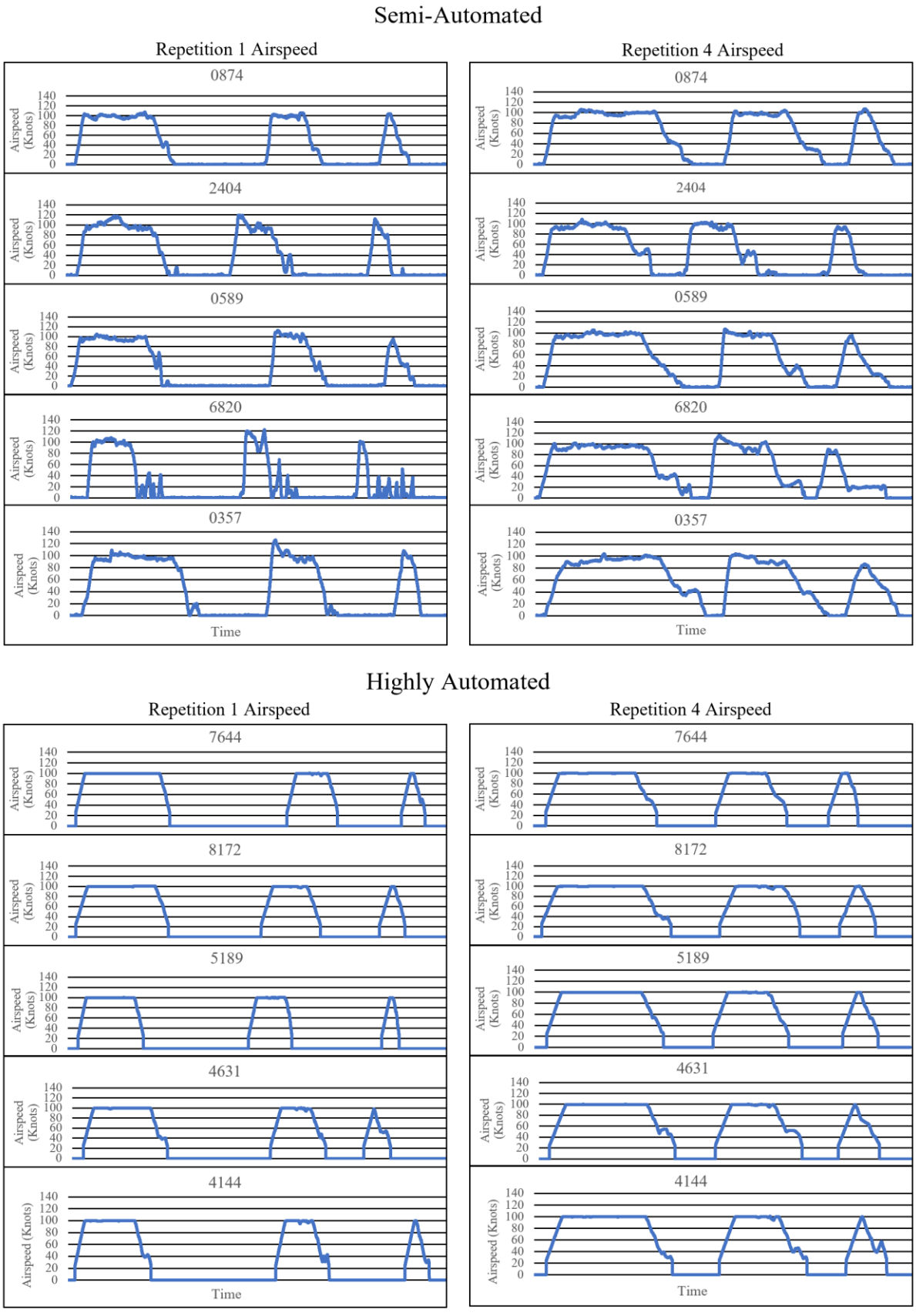
Overall, all participants were able to meet conventional standards of proficiency in the rate of acceleration during takeoffs despite different levels of automation between the two platforms. Where performance visibly differed was in the participants' abilities to reach the target airspeed by the end 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.

**Airspeed Performance: En Route Navigation**

In the highly automated platform, extremely high levels of proficiency were seen for maintaining the target airspeed during en route navigation. In fact, almost no deviations in airspeed were visible during most of the en route 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, like 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 en route 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. Only occasionally were major or unsafe increases or decreases of greater than 10 knots seen, 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 an insidious decrease in airspeed to 72 knots before starting their approach to the White House during the third leg. By the fourth repetition, his airspeed was more consistent around 100 knots, but he continued to show deviations from his 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, examination of airspeed during en route 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.


Semi-Automated
Repetition 1 Airspeed
Repetition 4 Airspeed
0874
2404
0589
6820
0357
Airspeed (Knots)
140
120
100
80
60
40
20
0
Time
Highly Automated
Repetition 1 Airspeed
Repetition 4 Airspeed
7644
8172
5189
4631
4144
Airspeed (Knots)
Time

**Airspeed Performance: Approaches & Landings**

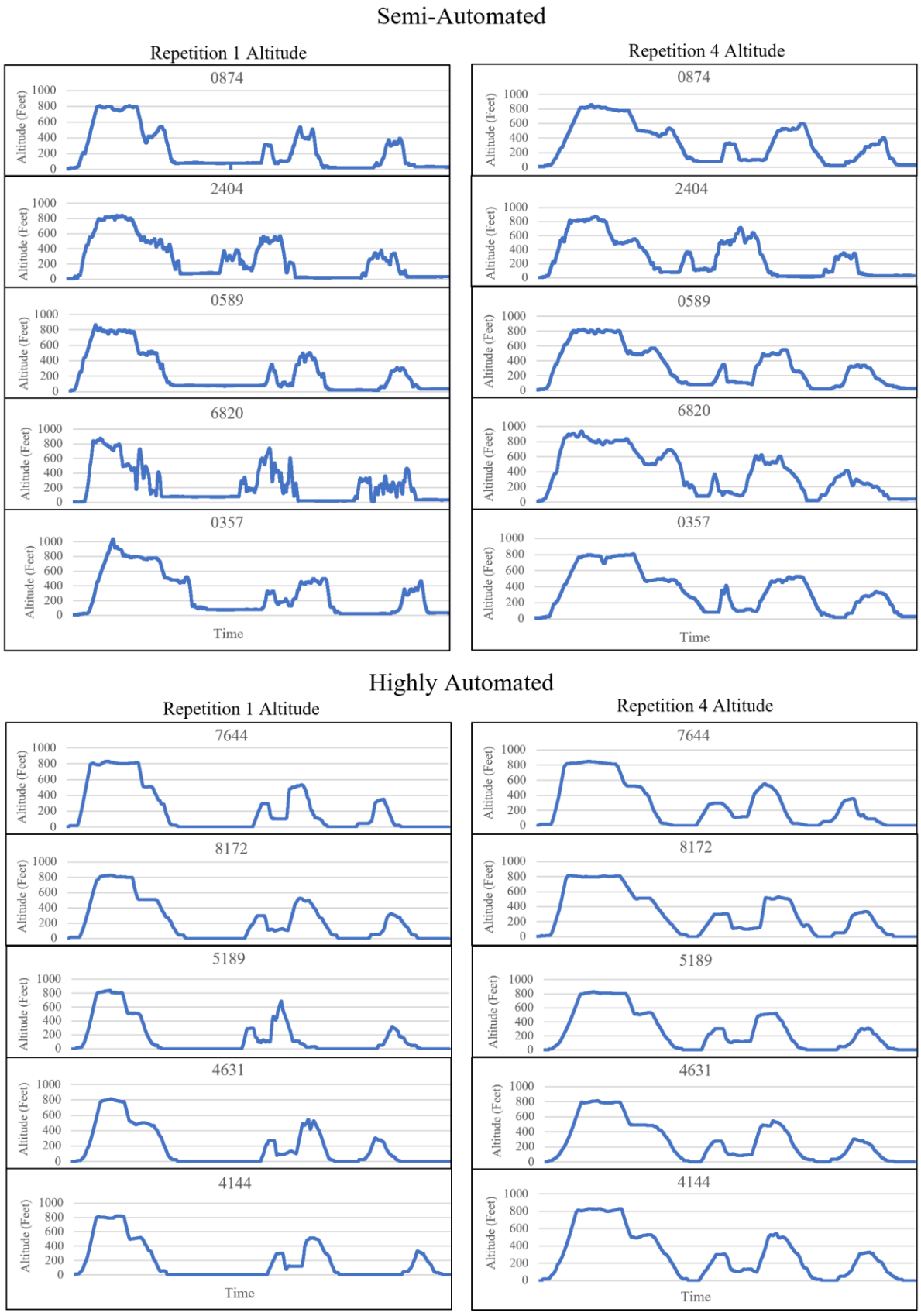
Airspeed during approaches and landings was less variable for the highly automated platform, as participants utilized a highly automated landing function that is not available in the semi-automated platform for landings. However, both platforms exhibit a "shelf" where airspeed stabilized or even briefly 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 at too high of an airspeed or altitude, causing a potentially hazardous condition. This instruction resulted in participants then 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 (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 use of the automation features of the platform—a result that may be attributed to either personal pilot preferences or to the type of training that 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. For example, for participant 0357 (Figure 3), 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**

In this section, we examine performance between the two platforms on altitude (in feet) during takeoffs, en route navigation, and approaches and landings across the three wing-borne legs for the first and fourth repetition of the profile (see Figure 4). 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
Repetition 1 Altitude
Repetition 4 Altitude
0874
2404
0589
6820
0357
Altitude (Feet)
1000
800
600
400
200
0
Time
Highly Automated
Repetition 1 Altitude
Repetition 4 Altitude
7644
8172
5189
4631
4144

**Altitude Performance: 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 eVTOL 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 likely related to the way in which 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 inputs 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.

**Altitude Performance: En Route 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 en route 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, 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, 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, examination of altitude during en route 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.

**Altitude Performance: Approaches & 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. 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.

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.

## LIMITATIONS

One main limitation of the present study is that conclusions rely primarily on visual inspection of a relatively small sample size. As a next step, the findings of the present study will be used to identify specific flight maneuvers to probe further with statistical analyses with a larger sample size ($n$ = 80 participants). We also plan to expand the study to examine differences in performance between pilots with fixed wing experience (represented here), helicopter pilots, and *ab initio* (i.e., individuals without flight experience). These studies will identify how the combination of various automated functions in the aircraft impact performance and learnability across a broad range of piloting experience.

Another limitation of the study is that it relies on the evaluation of mature prototypes still in the flight-testing stage. Some of the simulated flight characteristics may not be present in the final model. Furthermore, many of the augmentation/automation features are in development. Future studies should continue to evaluate and validate these aircraft features as they mature and companies begin flight testing.

## CONCLUSIONS

Overall, results demonstrated that the selected sample of experienced pilots exhibited proficiency in their command of airspeed and altitude across both the highly and semi-automated simulated eVTOL aircraft, even during their first repetition of the flight profile. By the time that participants completed the fourth repetition of the profile, having had

less than two hours of practice, most participants were able to perform within conventional standards of proficiency (i.e., within 5 knots of the target airspeed, within 100 feet of the target altitude) during most flight maneuvers. This demonstrates that both eVTOL aircraft, as emulated in simulators, are highly learnable for experienced pilots.

Performance between the two aircraft was not equivalent, which has bearing on training across eVTOLs with different levels of automation. Notably, the approach and landing phase showed the highest degree of variability in performance across both platforms, albeit for different reasons. In the highly automated platform, airspeed often did not decrease at a consistent rate, in stark contrast to the high performance on accelerations and maintenance of the target airspeed during other phases of flight. This pattern reflects participants' greater reliance on manual control of airspeed during approaches and landings over reliance on the machine-controlled automations either due to the training they received or personal preferences. The maturation of this automation feature and additional training may increase pilots' reliance on such machine-controlled features. Participants in the semi-automated platform also exhibited relatively lower performance on both airspeed and altitude during approaches and landings. During the transition from wing-borne to hovering in the semi-automated platform, the same human inputs to attitude control switch from affecting the altitude of the aircraft while wing-borne to affecting its speed while hovering. Similarly, the pilot must also shift from using one control to modulate power for airspeed while wing-borne to another control to modulate power for altitude while hovering. Thus, transitioning requires both a mental shift in what flight controls for attitude do as well as a physical shift to a different set of controls for power. Most participants showed drastic improvements between the first and fourth repetition of the profile on both altitude and airspeed performance during approaches and landings; however, most would have likely benefited from additional practice in making these mental and physical shifts during the transition. It is important to note that these deviations seen in the semi-automated aircraft tended to be very minor relative to conventional standards and in most cases still constituted proficient flight. Thus, early results demonstrate that emerging eVTOLs likely offer a degree of operational simplicity for future pilots. However, increasing levels of automation could provide advantages for UAM, creating a "smoother ride." A key training objective should include training pilots to take advantage of such automations.

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