The Influence of Short-Term Training and Prior Drone Experience on Simulated eVTOL Operation Performance with a Single-Hand Joystick

Yanbin Yang[1], Lei Lei[1], Haiyu Li[1], Dubo Huang[2], Dengbo He[1,*]

[1] Thrust of Intelligent Transportation, The Hong Kong University of Science and Technology (Guangzhou), Guangzhou, China

[2] Guangdong Huitian Aerospace Technology Co., Ltd., Guangzhou, China

[*] Corresponding author: Dengbo He (dengbohe@hkust-gz.edu.cn), No.1 Du Xue Rd, Nansha District, Guangzhou, Guangdong, China, 511453

Highlights:

- Short-term training significantly enhanced non-pilots' eVTOL control performance.
- Drone pilots generally outperformed non-pilots, showing experience transfer effects.
- Physiological stress and muscle effort decreased after training in both groups.
- Findings highlight the value of simplified controls for future eVTOL users.

Abstract:

As a promising solution for manned Urban Air Mobility (UAM), electric vertical takeoff and landing (eVTOL) aircraft are expected to be available to the general public in the near future. However, the existing control system in aviation might be too complex for the general public. Thus, eVTOL manufacturers have been revolutionizing eVTOL control systems in recent years, and the single-hand joystick control interface is one example. In a mixed-reality (MR), 6-degrees-of-freedom (6-DOF) flight simulator, we evaluated a novel single-hand joystick control interface for eVTOL aircraft, a solution that simulates drone operation and has already been adopted by a commercial eVTOL, and examined the effects of short-term operational training on potential users' operating performance. Given that the operating skills in similar domains might be transferable, participants with (drone pilots, n = 12) and without (non-pilots, n = 12) drone operating experience were recruited. All participants underwent a 30-minute MR-based eVTOL operation training. Comparing pilots' performance metrics before and after training showed improved eVTOL aircraft operational performance, supported by changes in electrocardiogram, electrodermal activity, respiration, and electromyography metrics. We also found that pilots performed better than non-pilots overall, and that non-pilots benefited more from the short-term training program. These findings highlight the feasibility of short-term training for basic eVTOL operational performance using a drone-like simplified control system and reveal, from a cognitive perspective, the transferability of operational skills between drone operation and eVTOL control.

Keywords: eVTOL; Drone experience; Mixed Reality; Simulator training

1. Introduction

As a projected mode of Urban Air Mobility (UAM) within city environments, the operation and deployment of electric vertical takeoff and landing (eVTOL) aircraft have drawn increasing attention. Unlike traditional aircraft such as helicopters or fixed-wing planes, which are equipped with complex human-machine interfaces and require expert pilots, thanks to fly-by-wire systems and automatic stabilization technologies that decouple complex attitude control into high-level command inputs, eVTOL systems are expected to progressively transfer from being operated by trained professionals to trained operators, and eventually to everyday users 0. Correspondingly, manufacturers plan to implement Simplified Vehicle Operations (SVO) to reduce required piloting skills and training demands, thereby improving flight performance while shortening training duration. For example, the Volocopter 0, a manned multirotor aircraft, uses a single-hand joystick to control an eVTOL aircraft, which can automatically hover when the stick is released. The personal aerial vehicle Jetson ONE 0 is equipped with a quad-axis joystick and an intelligent flight control computer, allowing pilots to manage altitude and direction effortlessly through joystick input.

Such an SVO makes simplified eVTOL aircraft control training possible. For example, ARIDGE 0 has announced its first commercially available eVTOL aircraft and claims that users can learn to fly it with five minutes of training. Although such claims may oversimplify training requirements, they motivate empirical investigation of how initial control performance develops through short-term training with simplified interfaces. Because eVTOL aircraft users may be less professional than carefully selected and well-trained pilots in the existing aviation industry, a customized training program is urgently needed and must be evaluated before eVTOL aircraft become available to the general public. Because eVTOL aircraft adopt a fundamentally different

design than helicopters or fixed-wing aircraft, existing pilot training programs may not fully support efficient eVTOL training.

Training unmanned aerial vehicle (UAV) operators may offer insights, as existing SVOs share substantial commonalities with UAM operations in flight control systems, which also involve joystick-based control. Specifically, both eVTOLs and UAVs operate under highly consistent control paradigms: stability is managed by onboard computers, and operators only need to issue simple directional commands. In this sense, eVTOLs can essentially be regarded as "large, passenger-carrying drones." Given these technological and interface similarities, drone piloting experience may transfer to eVTOL operations, providing a technical foundation and an opportunity for future training transfer and cross-domain pilot training.

Thus, in this study, using a VR-based eVTOL simulator, we aim to evaluate how short-term training affects pilots' basic eVTOL operations and whether it leads to satisfactory eVTOL control performance. Given the potential transferability of skills from UAV operation to eVTOL control, we also included drone pilots to assess whether and how UAV experience can benefit eVTOL basic control, laying an empirical foundation for selecting future eVTOL pilots and informing training-program design when new technologies are introduced. Specifically, the study provides empirical evidence on immediate operational performance improvements and experience-related differences under simplified vehicle controls, informing the design of introductory eVTOL training for operators with different experience backgrounds. We address the following research questions:

RQ1: How does short-term simulator-based training affect new users' and drone pilots' operational proficiency with an eVTOL using a single-hand joystick?

RQ2: Whether and how prior UAV-operating experience can be transferred to the basic

operation of an eVTOL that shares similar control paradigms?

Answering these questions requires a human cognition perspective: learning to control a novel aircraft interface is a cognitive skill acquisition process in which mental workload, attentional demand, and physiological arousal jointly constrain how quickly control schemas are formed, automated, and transferred across domains. This study therefore treats flight performance, autonomic responses, and subjective workload as converging indicators of the cognitive processes underlying eVTOL control learning. Finally, it is worth noting that this study focuses on the operational level of control skill—basic aircraft handling and route following under benign conditions—rather than on higher tactical and strategic skills such as situation awareness and decision-making under adverse or time-pressured conditions.

2. Literature Review

2.1 Operational innovation

eVTOL aircraft typically integrate helicopter-like vertical flight capabilities with fixed-wing airplane-style horizontal cruise performance. This inherent design complexity results in challenging control tasks across various flight phases, including hovering, transition, and cruising. Additionally, adopting distributed electric propulsion (DEP) significantly increases the difficulty of manual flight control. Consequently, reducing pilot workload and lowering training barriers have become critical bottlenecks in eVTOL aircraft development 0; 0). Traditional piloting skills, such as simultaneously managing multiple controls in helicopters, require considerable effort to learn and maintain proficiency. Therefore, SVO has emerged as an approach attracting substantial attention, aiming to make eVTOL piloting easier, safer, and less training-intensive.

SVO refers to leveraging automation to minimize the number of piloting skills an operator

must master while maintaining a necessary level of operational safety 0. Within the domain of aircraft control, SVO often specifically refers to Simplified Vehicle Controls (SVC). The concept of SVC can be traced back to the “Unified Control” system proposed by the UK Royal Aircraft Establishment (RAE) for vertical takeoff and landing (VTOL) aircraft 0. The primary control strategy involves intuitive and streamlined control devices, an equitable distribution of workload between hands, and minimizing hand-switching during critical flight phases. Further developing this concept, NASA Langley Research Center introduced a decoupled fly-by-wire control system known as “E-Z Fly” in the 1990s 0. This system was explicitly designed to simplify aircraft control, allowing novice pilots with limited flight experience to operate aircraft safely and effectively.

In recent years, numerous eVTOL prototypes and simulation systems have adopted single-hand joysticks and other simplified control schemes as core implementations of SVO 0 0 0. By integrating multi-axis inputs into a single primary control device for essential flight maneuvers such as climbing and turning, automated systems assume responsibility for tasks such as stability management and thrust allocation. Compared to conventional aircraft control, these simplified and automated controls can significantly reduce pilots’ physical and cognitive workload, especially in complex operational environments 0 0.

The introduction of SVO also implies significant transformations in pilot training models. Simplified flight controls and intuitive interfaces can effectively lower the training demands associated with piloting eVTOL aircraft 0. A study conducted by the U.S. Air Force Air Education and Training Command 0 evaluated experienced pilots’ learning curves using simulated eVTOL platforms characterized by varying levels of SVO automation. Results demonstrated that higher degrees of automation led to faster attainment of proficiency. Furthermore, pilots required

substantially less time to acquire basic stick-and-rudder skills when operating eVTOL aircraft equipped with SVO compared to traditional aircraft.

Subsequent studies have broadened the investigation of simplified controls beyond experienced pilots. Lee and Rakotomamonjy (2025) examined intuitive flight controls for novice operators using simulator tasks with varied difficulty. Janetzko et al. (2026) compared novices' and system designers' flight performance using standardized mission task elements, including transitions between rotary-wing and fixed-wing flight. In parallel, Kimura et al. (2024) investigated the instructor-operator station in an MR eVTOL training environment, evaluating factors that shape performance in simulator-based training (e.g., pilots' view for the instructor and the availability of eye-tracking data). These previous studies focused on the novices' control performance and the design of training environments. The present study complements these previous studies by examining changes in path-following performance before and after a short-term training protocol using a further simplified control interface, the single-hand joystick control. Accordingly, in response to RQ1, we hypothesize that participants will show improved path-following performance following short-term simulator-based training with our interface (**H1**).

2.2 Effects of prior flight experience (PFE) on eVTOL operation

In the field of aviation, pilot experience and domain knowledge are critical for safe operation. As a novel aviation technology, it is important to investigate how prior drone operating or flying experience affects performance in eVTOL operation, particularly in anticipation of future eVTOL pilot certification standards and training program development.

In previous research, it was found that more experienced pilots tended to adopt more efficient visual scanning strategies 0. Physiological responses also differed significantly between novice and

experienced pilots during flight tasks: novices tended to exhibit higher heart rates, greater cognitive load, and elevated physiological arousal, whereas experienced pilots demonstrated more regulated physiological responses 0. Given the potential implementation of SVO in eVTOL systems, prior experience with joystick-based control becomes especially relevant. For instance, Hewson et al. 0 0 compared electromyographic activity in experienced and novice pilots during various flight tasks and found that experienced pilots showed lower wrist muscle activation, indicating more efficient control strategies. Moreover, Hewson et al. 0 observed that after training, the muscle activation patterns of novice pilots became similar to those of experienced pilots. Regarding subjective workload, Maciejewska 0 found that expert drone operators consistently reported lower NASA-Task Load Index (NASA-TLX) scores than novices in tasks with varying levels of difficulty.

Simulator-based training, a widely adopted method in aviation, has also been shown to influence flight performance positively. Somerville et al. 0 found that novice drone pilots exhibited higher control accuracy following a period of structured simulator training, suggesting that even short-term simulated practice can enhance precision and efficiency in real-world flight tasks. Johnston and Catano 0 further found that both actual and simulated flight experience are associated with flight training success, and that simulator-based training could be used to identify candidates without prior experience who are likely to succeed in more advanced flight programs.

Various types of prior flight experience have been found to offer advantages in the context of eVTOL operation as well. For example, several simulation studies have evaluated eVTOL control performance across operators with different aviation backgrounds—such as rotary-wing pilots, fixed-wing pilots, and individuals with no prior flight experience. In another study, Emerson et al. 0 compared the performance of “ab initio” pilots (zero flight hours) with experienced pilots (>300

hours) on semi-automated and highly automated eVTOL simulation platforms. They found that experienced pilots outperformed novices overall, though both groups exhibited significant performance improvements after approximately two hours of training. Notably, novices using highly automated platforms achieved performance levels in certain tasks comparable to those of their more experienced counterparts. Similarly, Osman et al. 0 found that prior rotary-wing experience also offered specific transfer advantages in eVTOL operations such as hovering and vertical takeoff and landing.

However, although emergent single-hand joystick control in eVTOL aircraft mimics drone operation, no research has examined whether drone piloting experience benefits novice eVTOL operators in short-term training. Previous studies adopted different control interfaces and focused on different user groups. Thus, they may not inform the training needs of a production-ready interface for a user group that is not rare (i.e., those with some level of drone experience). Given that previous research has revealed skill transfer in aviation, we hypothesize that drone piloting experience can improve operational performance before training, but a short-term training program may plateau when participants use a similar control interface, the single-hand joystick control system (**H2**).

3. Method

3.1 Participants

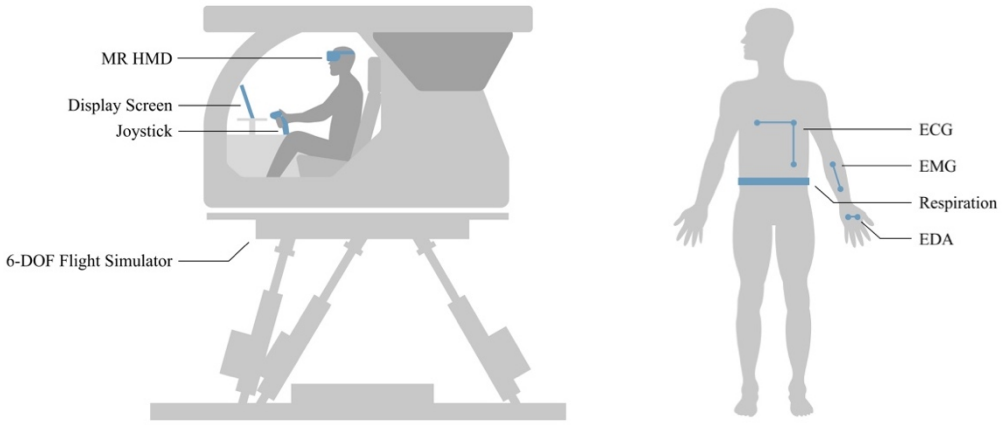
A total of 24 participants (5 females and 19 males), aged between 22 and 54 years (M = 29.54, SD = 7.56), were recruited. All participants were right-handed. The sample included 12 drone pilots and 12 participants without drone-operating experience (non-pilots). Drone pilots were defined as

individuals holding a Civil Unmanned Aircraft Operator Certificate issued by the Civil Aviation Administration of China (CAAC), a relevant qualification from another association or organization, or with no less than 44 hours of drone flight experience. None of the participants had prior experience operating an eVTOL simulator.

Given the use of a simulator with 6 degrees of freedom (6-DOF) and the MR technologies, before the experiment, participants were further screened for susceptibility to motion sickness (MS) to minimize its risk, using the Motion Sickness Susceptibility Questionnaire–Short Form (MSSQ-Short) 0 and the Visually Induced Motion Sickness Susceptibility Questionnaire (VIMSSQ) 0. Those with high susceptibility scores were excluded.

3.2 Apparatus

As shown in Figure 1a, the experiment was conducted using a six-degree-of-freedom (6-DOF) flight simulator developed by ARIDGE. The simulator incorporated MR technology to emulate an eVTOL cockpit environment, providing an immersive and realistic flight control experience. Due to commercial confidentiality, photos of the eVTOL simulator could not be presented. Participants wore a video-see-through head-mounted display (VST-HMD, model: Varjo XR-3), enabling them to see their own hands via VST cameras. They interacted with the eVTOL flight simulator using a single, realistic joystick that integrated buttons and multi-axis controls, facilitating intuitive flight manipulation. During flight, altitude was adjusted by pushing or pulling the control button—upward for ascent, downward for descent, and release to maintain altitude—while flight direction was controlled via multi-axis joystick movement. Releasing the joystick in any direction caused the aircraft to gradually decelerate and enter a hover state.



(a) (b)

Figure 1. Apparatus: (a) 6-DOF flight simulator; (b) Physiological sensors. ECG, EMG, and EDA stand for electrocardiogram, electromyography, and Electrodermal activity, respectively.

A display screen mounted on the central console provided participants with real-time flight status and navigational information. The left portion of the screen displayed integrated flight attitude data, including an artificial horizon to indicate pitch and roll angles, along with altitude, heading, airspeed, and vertical speed. The right portion showed a high-resolution satellite map, annotated with the current aircraft position, trajectory, and altitude information.

Participants' physiological responses were recorded using the wireless PhysioLab system by Info Tech, integrated with the Human Research Tool software suite. As illustrated in Figure 1b, electrocardiography (ECG), electromyography (EMG), respiration, and electrodermal activity (EDA) data were collected at a rate of 1000 Hz. ECG signals were recorded using three electrodes, with the positive and negative electrodes placed at the midpoints between the clavicle and the nipple on the left and right sides, respectively, and the ground electrode attached to the lower left rib margin. EMG signals were collected with two non-polarized electrodes positioned at both ends of the

forearm muscle, which is most activated when the dominant hand clenched a fist. EDA signals were acquired using two non-polarized electrodes placed on the non-dominant palm, one placed below the thenar eminence and the other below the ring and little fingers. Respiration was measured with a belt sensor secured around the abdomen at the site of maximal respiratory movement.

3.3 Experimental design and procedures

The study used a mixed design, with drone-operating experience as a between-subjects factor and assessment session (pre-training and post-training) as a within-subjects factor. Both groups completed the same practice protocol. Before the experiment, participants were instructed to maintain regular sleep and to refrain from consuming alcohol or caffeinated beverages the day before the experiment.

Figure 2 provides an overview of the experimental procedure. Upon arrival, participants first received a brief introduction to the experimental tasks. They then reviewed and signed an informed consent form and had the opportunity to ask questions to ensure full understanding and voluntary participation. Next, we applied physiological sensors: three ECG electrodes were attached to the chest, two EMG electrodes were placed on the flexor carpi ulnaris (FCU) of the dominant forearm, two EDA electrodes were affixed to the palm of the non-dominant hand, and a respiration belt was secured around the abdomen.

Before the formal experiment began, participants entered the simulator cockpit and underwent a 5-minute resting period to stabilize and measure baseline physiological signals. During this phase, participants sat with their eyes closed, hands resting palms-up on their knees. Next, they received about 5 minutes of verbal instruction on flight control and completed a 5-minute familiarization phase in the simulator. This phase included basic joystick operations (pitch, roll, and yaw control),

interpretation of flight instruments (airspeed, altitude, pitch, and roll), and orientation to the experimental flight route.

As shown in Figure 2, the formal experimental session comprised a pre-training assessment, training part (including approximately 30 minutes of axis-focused maneuver training and an untimed full-route review flight), and a post-training assessment. Two 5-minute breaks were provided between the three axis-focused training blocks. The approximately 30-minute training duration excluded these breaks. Both pre-training and post-training assessments used the same predefined riverbank route in a clear-weather valley scenario. After completing the post-training assessment, participants received 150 RMB in monetary compensation. This study was approved by the Human Research Ethics Committee of The Hong Kong University of Science and Technology (Guangzhou) (Protocol No.: HSP-2024-0084).

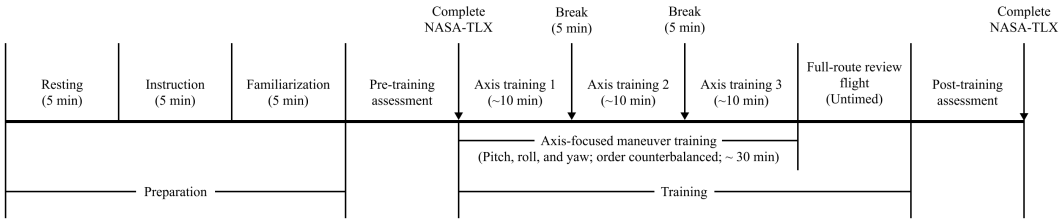


Figure 2. Experimental procedure. Axis-focused maneuver training comprised pitch, roll, and yaw exercises, with approximately 10 minutes allocated to each axis and training order counterbalanced across participants. An additional untimed full-route review flight was conducted before the post-training assessment. NASA-TLX was administered after each assessment.

3.3.1 Training program

As shown in Figure 2, the training program comprised three axis-focused maneuver (axis training) exercises followed by a full-route review flight.

Axis training along 3 directions: The maneuver exercises focused on pitch, roll, and yaw

control, with approximately 10 minutes allocated to each axis. Their order was counterbalanced across participants to reduce potential order effects. During each exercise, the experimenter verbally specified a target pitch angle, roll angle, or heading, and participants manipulated the joystick to achieve the requested aircraft attitude or heading. Participants monitored the corresponding cockpit instrument readings and adjusted their inputs to approach the target. Pitch and roll exercises involved targets in both directions, while yaw exercises involved heading changes to the left and right. The experimenter provided corrective verbal feedback when participants used an incorrect input or had difficulty reaching the target, while participants retained control of the joystick throughout. These exercises were intended to familiarize participants with the relationship between joystick inputs and changes in aircraft attitude and heading, providing a foundation for directional control during the subsequent path-following task. Practicing target attainment across the three axes was intended to help participants regulate their control inputs and make corrections when following the riverbank route and executing the U-turn. The exercises therefore focused on component control skills relevant to route following, rather than practice of the assessment route itself. The approximately 10-minute duration for each axis represented a fixed practice allocation rather than a proficiency-based stopping criterion.

Full-route review flight: After completing the approximately 30-minute maneuver training, participants performed an additional untimed review flight along the entire route used in the pre- and post-training assessments (Figure 3). This flight integrated the separately practiced maneuvers into the complete task sequence, including takeoff, ascent to the target altitude of 120 m, outbound riverbank following, a U-turn at the designated waypoint, and return along the opposite riverbank.

In this review flight and the assessment flights, the reference trajectory generated by an

experienced pilot was presented within the MR environment as a continuous ground-based visual guide. The recorded trajectory was converted into the simulated environment's coordinate system, and its horizontal positions were projected onto the terrain surface and connected to form a visible line that remained fixed relative to the terrain. Participants could observe the line ahead of and below the aircraft through the cockpit windows and use it to follow the designated horizontal route, while monitoring the altitude instrument to maintain the instructed flight altitude of 120 m. The external scene included the river, riverbanks, and surrounding valley. Participants could turn their heads to inspect these features through the front and side windows, while opaque cockpit structures, including the floor, occluded the corresponding portions of the scene. No additional navigation markers or directional arrows were provided.

The experimenter clarified the route sequence when necessary but did not provide continuous maneuver instructions. The review flight was intended to consolidate participants' familiarity with the route and the coordinated use of the controls before the post-training assessment. Its duration was additional to the approximately 30 minutes allocated to the axis-focused exercises.

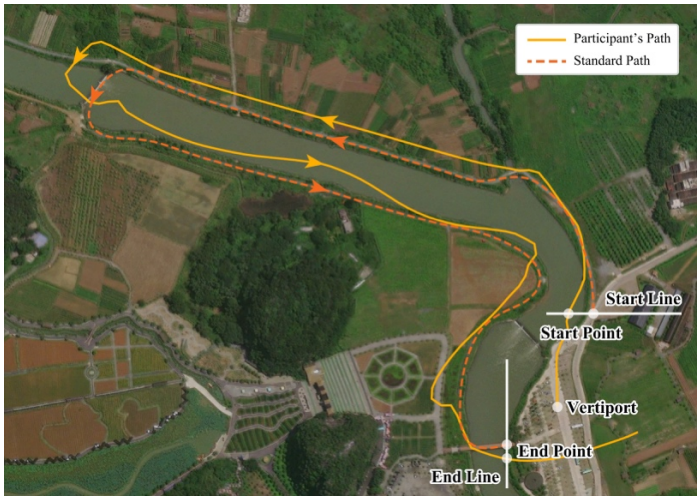


Figure 3. Assessment route showing the reference trajectory generated by an experienced pilot (dashed

line) and an example participant trajectory (solid line). The start and end locations and the start and end lines are indicated. Performance measures were calculated from horizontal trajectory deviations; altitude-control accuracy was not quantified.

3.3.2 Assessment flights

As shown in Figure 3, during the assessment, participants were instructed to take off from the starting vertiport, ascend to 120 m, maintain that altitude while following the outbound riverbank route, execute a U-turn at the designated waypoint, and return along the opposite riverbank to the starting location. The task therefore involved route following and turning in addition to altitude maintenance. During the assessments, participants controlled the aircraft themselves, and the experimenter did not provide continuous maneuver guidance or corrective feedback. Participants selected their own flight pace; no time limit was imposed, and accuracy was emphasized. Because altitude was not available in the recorded trajectory data, the performance analysis assessed only the horizontal component of route following. Upon completion of each assessment flight, participants completed the NASA-TLX questionnaire. Overall, by design, this assessment task instantiated a basic operational-level skill—route following with altitude managed by the flight-control system—rather than a full urban-mobility mission; it therefore provides a constrained but controlled testbed for examining initial adaptation to the simplified joystick interface.

3.4 Extracted variables

3.4.1 Performance measures

We used path error during flight—defined as deviation from the intended route—to evaluate participants' performance 0. Three metrics were computed to quantify this deviation: mean path error (ME), standard deviation of path error (SD), and root mean square error (RMSE). As shown

in Figure 3, the standard path for subsequent comparative analyses was defined as the trajectory generated by an experienced pilot performing a smooth flight along the predetermined route. The raw flight trajectories flown by the participants were converted from geographic coordinates to Universal Transverse Mercator (UTM) coordinates to obtain planar X and Y values. Because the simulator's flight control system did not record altitude, this study focused exclusively on planar path-following performance.

3.4.2 Physiological measures

Physiological measures were collected as complementary indicators of autonomic arousal and motor activity during the assessments. These measures may vary with task demands, familiarity, emotional responses, respiration, and physical activity 0. They were therefore treated here as indirect indices of cognitive workload and attentional engagement, that is, of the cognitive cost of manual flight control. In this study, we mainly focused on pilots' ECG-, EMG-, EDA-, and respiration-related metrics throughout the flight. All metrics were extracted using the NeuroKit2 Python package 0.

Specifically, for ECG signals, we extracted heart rate variability (HRV) metrics, including time-domain and frequency-domain measures. Among HRV time-domain metrics, the standard deviation of NN intervals (SDNN) and the square root of the mean-squared differences between successive NN intervals (RMSSD) have been validated as effective indicators of mental workload in pilots and were therefore adopted in our study 0. Among the frequency-domain metrics, we adopted the low-frequency (0.04–0.15 Hz) to high-frequency (0.15–0.4 Hz) power ratio (LF/HF), validated for predicting excessive stress and arousal during flight, as a secondary indicator of task difficulty 0.

As for respiratory metrics, the respiratory rate (RR) was included as it was widely adopted as an indicator of pilot stress and workload 0 0. For EDA-related metrics, we included the tonic (skin conductance level, SCL) and phasic (skin conductance responses, SCR) components, as they are widely used to measure physiological arousal among pilots 0 0. Specifically, phasic events exceeding a 0.01 μS amplitude threshold were identified as SCRs 0. The number of SCR rate (SCRs/min) was calculated by dividing the number of SCRs in the window by the window duration in seconds, then multiplying by 60.

Although the overall physical demands of piloting are relatively low, flight control remains a complex task that requires high levels of motor coordination. Therefore, quantifying muscle activation during control tasks is also important. Thus, the root mean square (RMS) of the EMG signal was also adopted to characterize the amplitude of forearm muscle activation during joystick operation, given that it was widely used to assess muscle fatigue among helicopter pilots 0 0.

3.4.3 Subjective workload

Workload has a significant impact on pilot training outcomes and flight performance 0. Thus, in the context of pilot training, changes in workload can be used to evaluate training effectiveness 0. In our study, the NASA-TLX developed by the National Aeronautics and Space Administration 0 was used to evaluate perceived workload during flights. We adopted the simplified, unweighted version of NASA-TLX, known as Raw TLX (RTLX), to reduce the administration time 0. Each subscale was rated on a 21-point line anchored by bipolar descriptors (‘Low’–‘High’), without numerical labels, and later scaled to a 0–100 range, with higher scores indicating higher perceived load.

3.5 Statistical analysis

The mixed linear models were built to examine the effects of Group (drone pilots and non-pilots), Flight Session (pre-training assessment and post-training assessment), and their interaction (Group × Flight Session) on participants' operational performance, physiological responses, and subjective workload, with repeated measures on each participant accounted for by Generalized Estimating Equations (GEE). All models were implemented using the Proc Mixed procedure in "*SAS OnDemand for Academics*," with the covariance structure specified as compound symmetry (CS). For all fixed effects reaching statistical significance ($p < .05$), Tukey-adjusted post-hoc pairwise comparisons were performed.

4. Results

4.1 Performance

The results of performance metrics are summarized in Table 1. Summary of model results for performance metrics.. The interaction effects of group and flight session were observed for all performance-related metrics.

Table 1. Summary of model results for performance metrics.

IV	Group	Flight Session	Group × Flight Session
DV: ME	F(1,22) = 32.59	F(1,22) = 68.18	F(1,22) = 23.93
(F-value, *p*)	$p < .0001$*	$p < .0001$*	$p < .0001$*
DV: SD	F(1,22) = 27.82	F(1,22) = 68.39	F(1,22) = 21.83
(F-value, *p*)	$p < .0001$*	$p < .0001$*	$p = .0001$*
DV: RMSE	F(1,22) = 32.54	F(1,22) = 83.12	F(1,22) = 28.74
(F-value, *p*)	$p < .0001$*	$p < .0001$*	$p < .0001$*

Note: In this table and following tables, the * and the shaded cell marks significant results ($p < .05$)

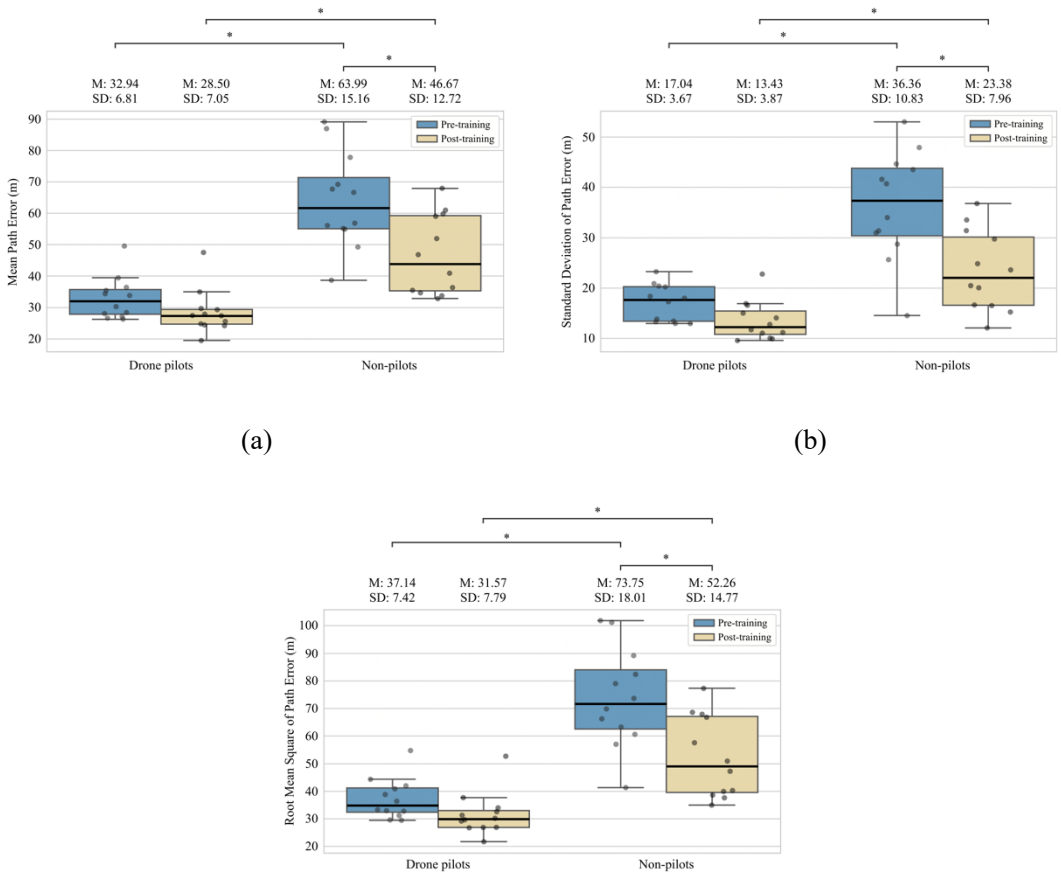


Figure 4. Difference in performance metrics between the drone pilot group and the non-pilot group before and after training: (a) ME, (b) SD, and (c) RMSE. Note: In this figure and the following figures, the * marks significant effects ($p < .05$), and boxplots present the minimum, 1st quartile, median, 3rd quartile, and maximum, and the mean (M) and standard deviation (SD) are on top of each bar.

Figure 4a shows the ME for each group across two flight sessions. Specifically, the non-pilot group demonstrated a significant reduction in ME after training, with an estimated difference (Δ) of -17.33, 95% confidence interval (95% CI) of [-22.50, -12.15], $t(22) = -9.30$, $p < .0001$, whereas no significant change was observed among drone pilots. Significant between-group differences were also found in both pre-training assessment (Δ = -31.06, 95% CI = [-43.57, -18.54], $t(22) = -6.89$, $p < .0001$) and post-training assessment (Δ = -18.16, 95% CI = [-30.68, -5.65], $t(22) = -4.03$, $p = .003$), with pilots exhibiting a lower ME compared to the non-pilots.

Figure 4b shows the variability in SD across groups and flights. The non-pilots showed a decreased SD (Δ = -12.99, 95% CI = [-16.93, -9.05], $t(22) = -9.15$, $p < .0001$) after training, while no significant change was detected among drone pilots. Between-group differences were also significant in both pre-training assessment (Δ = -19.33, 95% CI = [-27.52, -11.13], $t(22) = -6.55$, $p < .0001$) and post-training assessment (Δ = -9.95, 95% CI = [-18.14, -1.76], $t(22) = -3.37$, $p = .01$), with pilots showing a lower SD compared to the non-pilots.

As shown in Figure 4c, RMSE values indicate differences in overall trajectory accuracy between groups and across flights. The non-pilots exhibited a significant decrease in RMSE (Δ = -21.49, 95% CI = [-27.32, -15.66], $t(22) = -10.24$, $p < .0001$) after training, while no significant difference was observed for drone pilots. Between-group comparisons indicated significant differences in both pre-training assessment (Δ = -36.60, 95% CI = [-51.14, -22.06], $t(22) = -6.99$, $p < .0001$) and post-training assessment (Δ = -20.69, 95% CI = [-35.23, -6.15], $t(22) = -3.95$, $p = .004$), , with pilots showing a lower RMSE compared to the non-pilots.

4.2 Physiological metrics

Table 2 presents the model results for physiological responses.

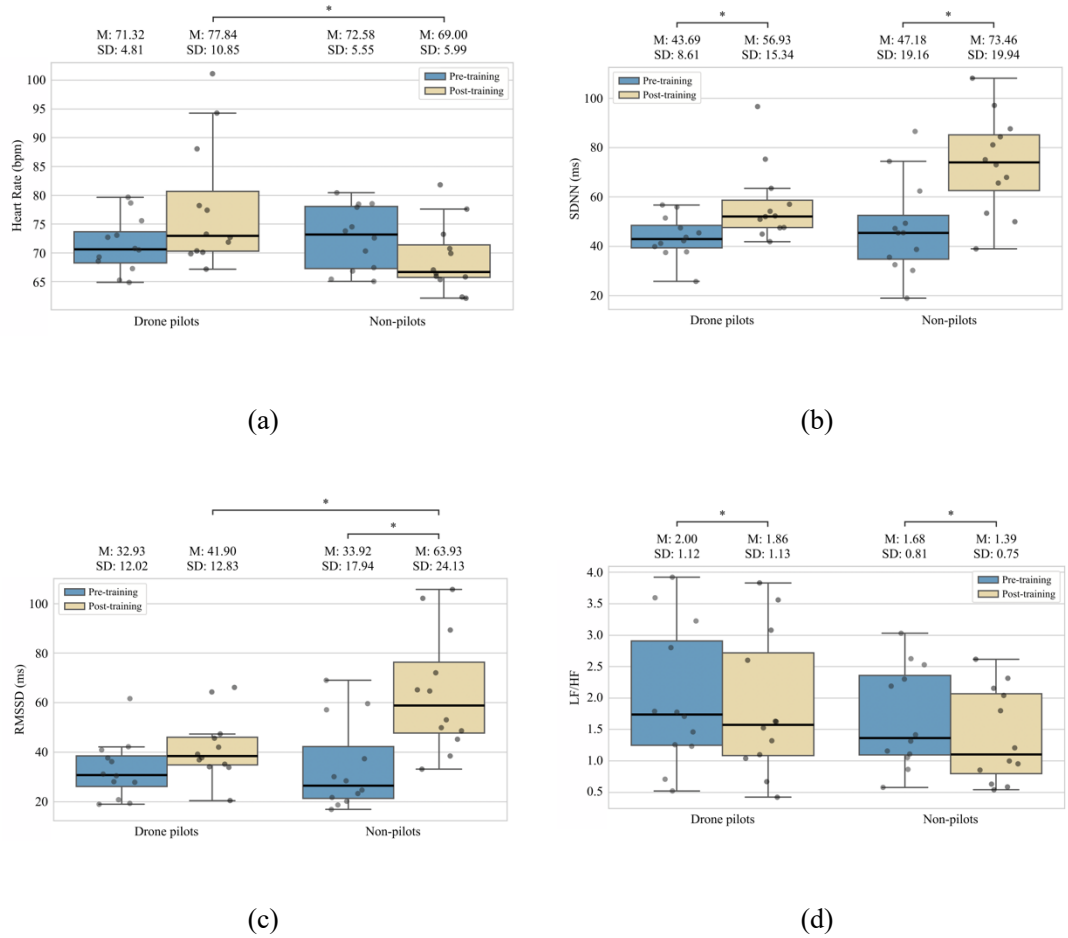
Table 2. Summary of model results (physiological responses).

IV	Group	Flight Session	Group × Flight Session
DV: HR	F(1,22) = 3.41	F(1,22) = 0.48	F(1,22) = 5.74
(F-value, *p*)	*p* = .08	*p* = .5	*p* = .03*
DV: SDNN	F(1,22) = 2.58	F(1,22) = 66.52	F(1,22) = 7.25
(F-value, *p*)	*p* = .12	*p* < .0001*	*p* = .01*
DV: RMSSD	F(1,22) = 3.99	F(1,22) = 21.88	F(1,22) = 6.38
(F-value, *p*)	*p* = .06	*p* = .0001*	*p* = .02*
DV: LF/HF	F(1,22) = 1.09	F(1,22) = 116.65	F(1,22) = 15.00

(F-value, *p*)	*p* = .3	*p* < .0001*	*p* = .0008*
DV: EMG RMS	F(1,22) = 13.43	F(1,22) = 48.55	F(1,22) = 8.81
(F-value, *p*)	*p* = .001*	*p* < .0001*	*p* = .007*
DV: SCR Rate	F(1,22) = 5.37	F(1,22) = 97.33	F(1,22) = 17.47
(F-value, *p*)	*p* = .03*	*p* < .0001*	*p* = .0004*
DV: Mean SCL	F(1,22) = 6.13	F(1,22) = 68.64	F(1,22) = 9.82
(F-value, *p*)	*p* = .02*	*p* < .0001*	*p* = .005*
DV: RR	F(1,22) = 1.10	F(1,22) = 110.66	F(1,22) = 18.04
(F-value, *p*)	*p* = .3	*p* < .0001*	*p* = .0003*

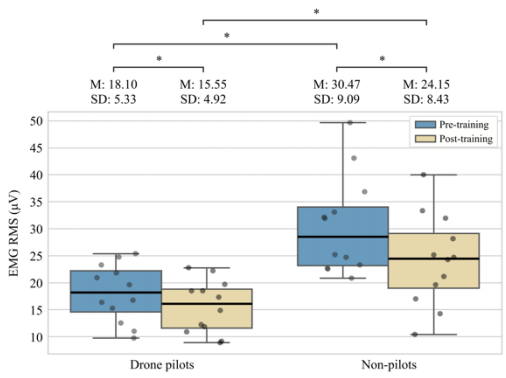
4.2.1 ECG-related metrics

As shown in Figure 5, we observed an interaction effect between group and flight session on participants' HR, SDNN, RMSSD, and LF/HF. Specifically, in post-training, a significant difference in HR was observed between the groups, with drone pilots showing significantly higher HR levels than non-pilots (Δ = 8.84, 95% CI = [0.67, 17.00], $t(22) = 3.01$, $p = .03$). Further, SDNN increased from pre-training assessment to post-training assessment for both drone pilots (Δ = -13.24, 95% CI = [-22.75, -3.72], $t(22) = -3.86$, $p = .004$) and non-pilots (Δ = -26.28, 95% CI = [-35.80, -16.77], $t(22) = -7.67$, $p < .0001$). At the same time, the non-pilots showed an increase in RMSSD (Δ = 30.01, 95% CI = [13.65, 46.38], $t(22) = 5.09$, $p = .0002$) from pre-training assessment to post-training assessment and a significant between-group difference emerged during post-training assessment (Δ = -22.03, 95% CI = [-41.77, -2.29], $t(22) = -3.10$, $p = .03$), with drone pilots exhibiting lower RMSSD. Finally, a significant decrease in LF/HF was found from pre-training assessment to post-training assessment for both drone pilots (Δ = -0.14, 95% CI = [-0.21, -0.06], $t(22) = -4.90$, $p = .0004$) and non-pilots (Δ = -0.29, 95% CI = [-0.37, -0.21], $t(22) = -10.38$, $p < .0001$). No other significant effects were observed for ECG-metrics ($p > .05$).



1 Figure 5. Difference in ECG-related metrics between the drone pilot group and the non-pilot group
2 before and after training: (a) HR, (b) SDNN, (c) RMSSD, and (d) LF/HF.

3 **4.2.2 EMG-related metric**



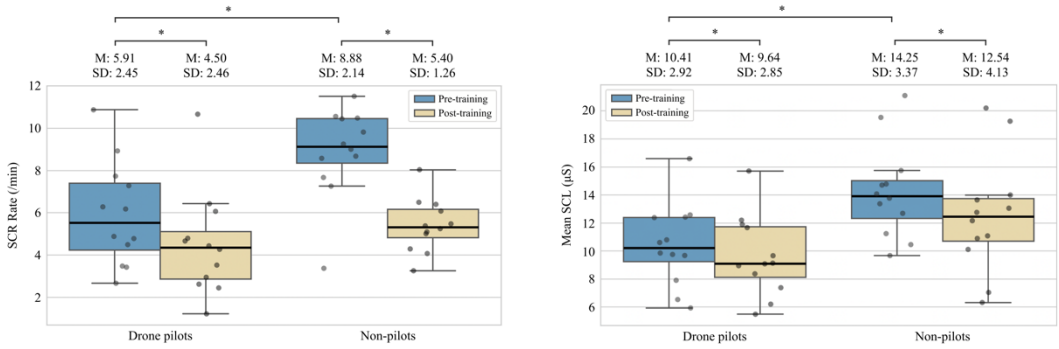
4 Figure 6. Difference in EMG RMS between the drone pilot group and the non-pilot group before and
5 after training.

6 Figure 6 illustrates the interaction effects of group and flight session on RMS values.

Specifically, RMS decreased from pre-training assessment to post-training assessment among both drone pilots (Δ = -2.55, 95% CI = [-5.05, -0.05], $t(22)$ = -2.83, p = .0449) and non-pilots (Δ = -6.33, 95% CI = [-8.83, -3.83], $t(22)$ = -7.03, p < .0001). Additionally, significant between-group differences were observed during both pre-training assessment (Δ = -12.38, 95% CI = [-20.51, -4.24], $t(22)$ = -4.22, p = .002) and post-training assessment (Δ = -8.59, 95% CI = [-16.73, -0.46], $t(22)$ = -2.93, p = .04), with drone pilots exhibiting lower RMS values than non-pilots in both assessments.

4.2.3 EDA-related metrics

Significant interactions of group and training session were observed for SCR and SCL. Specifically, as illustrated in Figure 7a, both drone pilots (Δ = -1.41, 95% CI = [-2.39, -0.44], $t(22)$ = -4.02, p = .003) and non-pilots (Δ = -3.48, 95% CI = [-4.46, -2.51], $t(22)$ = -9.93, p < .0001) exhibited significantly lower SCR after training. At the same time, in pre-training assessments, non-pilots exhibited higher SCR compared to pilots (Δ = 2.97, 95% CI = [0.55, 5.39], $t(22)$ = 3.41, p = .01).



(a) (b)

Figure 7. Difference in EDA-related metrics between the drone pilot group and the non-pilot group before and after training: (a) SCR Rate and (b) Mean SCL.

As shown in the Figure 7b, both groups showed lower SCL after training (drone pilots: Δ = -0.77, 95% CI = [-1.36, -0.18], $t(22) = -3.64$, $p = .007$; non-pilots: Δ = -1.71, 95% CI = [-2.31, -1.13], $t(22) = -8.07$, $p < .0001$). At the same time, in pre-training assessments, pilots exhibited a 3.84-unit lower SCL compared to non-pilots, 95% CI = [0.04, 7.65], $t(22) = 2.80$, $p = .047$.

4.2.4 Respiration-related metric

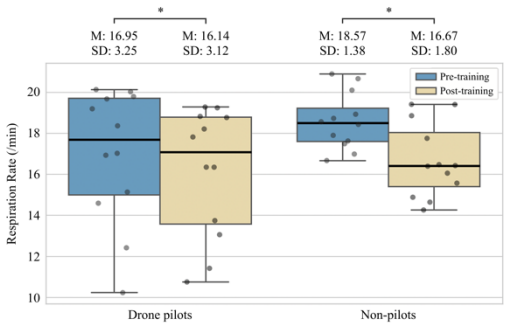


Figure 8. Difference in RR indicators between the drone pilot group and the non-pilot group before and after training.

As shown in Figure 8, an interaction effect between group and training session was observed for RR. Both groups exhibited significant decreases in RR from pre-training assessment to post-training assessment, but to different extents (drone pilots: Δ = -0.81, 95% CI = [-1.31, -0.30], $t(22) = -4.44$, $p = .001$; non-pilots: Δ = -1.90, 95% CI = [-2.41, -1.40], $t(22) = -10.44$, $p < .0001$).

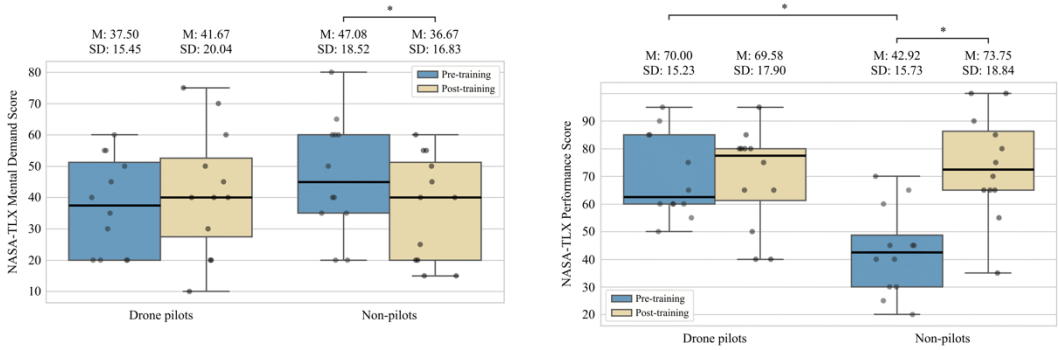
4.3 Subjective workload

As summarized in Table 3, and in Figure 9a, the non-pilot group showed a significant reduction in Mental Demand after training (Δ = -10.42, 95% CI = [-19.16, -1.68], $t(22) = -3.31$, $p = .02$). Further, as shown in Figure 9b, the non-pilot group experienced significantly higher Performance scores after training (Δ = 30.83, 95% CI = [17.47, 44.20], $t(22) = 6.41$, $p < .0001$), and the drone

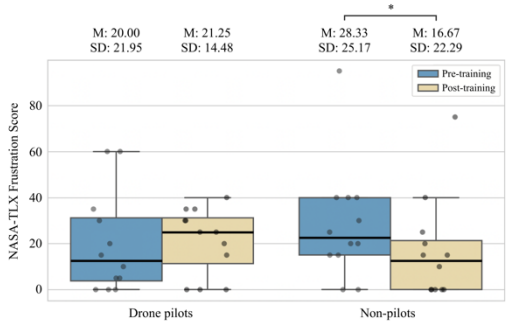
pilots had significantly higher Performance scores than non-pilots prior to training (Δ = 27.08, 95% CI = [7.82, 46.34], $t(22) = 3.90$, $p = .004$). Next, as shown in Figure 9c, it was found that the non-pilot group had lower Frustration scores after training (Δ = -11.67, 95% CI = [-22.77, -0.56], $t(22) = -2.92$, $p = .04$). All other comparisons were not statistically significant ($p > .05$). In addition, a significant main effect of group was found for Temporal Demand, with the drone pilot group reporting lower scores than the non-pilot group (Δ = 16.04, 95% CI = [4.45, 27.63], $t(22) = 2.87$, $p = .009$), whereas the interaction effect was not significant, as shown in Figure 10.

Table 3. Summary of model results (NASA-TLX).

IV	Group	Flight Session	Group × Flight Session
DV: Mental Demand (F-value, *p*)	F(1,22) = 0.11 *p* = .7	F(1,22) = 1.97 *p* = .2	F(1,22) = 10.74 *p* = .003*
DV: Physical Demand (F-value, *p*)	F(1,22) = 0.06 *p* = .8	F(1,22) = 1.27 *p* = .3	F(1,22) = 1.27 *p* = .3
DV: Temporal Demand (F-value, *p*)	F(1,22) = 8.24 *p* = .009*	F(1,22) = 0.14 *p* = .7	F(1,22) = 0.29 *p* = .6
DV: Performance (F-value, *p*)	F(1,22) = 3.59 *p* = .07	F(1,22) = 19.97 *p* = .0002*	F(1,22) = 21.08 *p* = .0001*
DV: Effort (F-value, *p*)	F(1,22) = 0.01 *p* = .94	F(1,22) = 0.64 *p* = .4	F(1,22) = 0.07 *p* = .8
DV: Frustration (F-value, *p*)	F(1,22) = 0.05 *p* = .8	F(1,22) = 3.39 *p* = .08	F(1,22) = 5.22 *p* = .03*



(a) (b)



(c)

Figure 9. Difference in NASA-TLX scores between the drone pilot group and the non-pilot group before and after training: (a) Mental Demand, (b) Performance, and (c) Frustration.

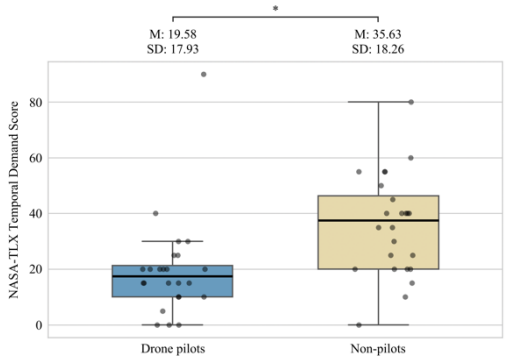


Figure 10. Difference in NASA-TLX Temporal Demand score between the drone pilot group and the non-pilot group.

5. Discussion

5.1 Training effect

First, in response to RQ1 and in line with our hypothesis (H1), we found that short-term training was effective in improving operational performance and reducing task-induced stress, particularly among non-pilot participants. Specifically, all three path error metrics (ME, SD, RMSE) improved significantly after training among non-pilots, indicating enhanced control quality with short-term training. Subjectively, non-pilots also reported lower Mental Demand and Frustration scores, along with higher Performance ratings on the NASA-TLX, reflecting reduced perceived workload and increased confidence following training. This noticeable training effect may be attributed to the simplified control systems adopted in the simulated eVTOL, echoing previous research (0. From a human cognition standpoint, this pattern indicates that short-term training lowered the cognitive load of joystick control: as control actions became automated, fewer attentional resources were required, leaving capacity for trajectory monitoring and decision-making. The lack of a training effect among pilots, however, may be due to their already high proficiency in operating drones with joysticks, which we discuss later when answering RQ2.

Beyond performance metrics and self-reported performance, we also observed significant physiological changes after training, providing further evidence regarding the effectiveness of the short-term training for both pilots and non-pilots. Specifically, for ECG-related metrics, RMSSD increased significantly after training among non-pilots, indicating enhanced parasympathetic activity and a more relaxed physiological state 0. The significant reduction in LF/HF and increase in SDNN among both pilots and non-pilots further support a parasympathetic-dominant trend 0 0. In parallel, both SCR and SCL levels dropped significantly after training in both groups, reflecting decreased physiological arousal and increased task familiarity 0 0 0. RR and RMS also decreased notably during the post-training assessment in both groups, suggesting that training might have

supported more efficient and stable breathing strategies to manage task load 0 0, and more efficient and less effortful motor strategies 0. Note that physiological responses can be influenced by multiple factors, including familiarity, habituation, breathing patterns, and motor activity. They therefore provide complementary information about participants' state during task execution rather than independent confirmation of control-skill acquisition. Together, these autonomic and muscular changes, along with performance changes, map onto a cognitive skill acquisition account: with practice, controlled, effortful processing gives way to automatic, low-load processing.

Finally, it should be noted that the training effects may differ among different user groups. Specifically, the effect of training on drone pilots, while present, was more modest. In terms of flight performance, drone pilots did not show significant changes in ME, SD, or RMSE following training, indicating a performance plateau. No significant changes in subjective workload ratings were observed among pilots, suggesting that pilots had already formed consistent self-perceptions of task demands and were less influenced by additional short-term training. Further, although SDNN increased and LF/HF, SCR, SCL, RMS, and RR decreased after training among pilots, the magnitude of change was smaller than that observed in non-pilots, likely because the pilots already had stable autonomic regulation and limited room for improvement. However, again, it should be noted that the observed changes in physiological measures followed a protocol combining structured maneuver training and full-route practice. Repeated task execution and increasing familiarity with the simulator and route may have contributed alongside the instructional content. Future studies with larger sample sizes and baseline groups may be further needed to validate the findings based on physiological measures.

Overall, the within-group analyses in pre-training assessments and post-training assessments

indicate that short-term training can lead to observable operational performance improvements, particularly for individuals with limited prior experience. For drone pilots, the training led to subtler optimizations, reflecting individual differences and the possibility of experience transfer between drone operation and eVTOL control in terms of basic operational skills.

5.2 Experience transfer

In response to RQ2 and supporting H2, we found that pilots' eVTOL operational task performance was overall higher than that of non-pilots, and their improvement after training was less pronounced than that of non-pilots. As mentioned previously, this is not surprising, as the simplified single-hand joystick control mimics the operation of drones for which the pilots were trained.

Echoing the performance metrics, we also observed interaction effects across multiple physiological indicators, suggesting that prior drone piloting experience may also have a measurable impact on pilots' adaptation to eVTOL operation. Specifically, drone pilots exhibited significantly higher HR and lower RMSSD than non-pilots during the post-training assessment. This may be because pilots were more aware of flight risks; thus, their stress level, as reflected by HR 0 and RMSSD 0 0, did not decrease even after training. In contrast, non-pilots may have felt more confident in their skills after training, leading to lower stress. In other words, non-pilots may have exhibited a shift toward more relaxed parasympathetic regulation after training. Consistent with the trends in ECG-related metrics, non-pilots also showed significantly higher SCR and mean SCL than pilots prior to training, suggesting greater physiological arousal and stress 0 0 0 in response to unfamiliar tasks. However, no significant differences in SCR or SCL between pilots and non-pilots were observed after training, again indicating relaxed parasympathetic regulation after training

among non-pilots. Supporting these physiological responses, drone pilots also self-reported higher performance before training than non-pilots, whereas non-pilots' self-reported performance scores increased dramatically after training, narrowing the gap between pilots and non-pilots.

However, it should be noted that, though psychologically more relaxed, drone pilots consistently exhibited lower RMS values across both flights, implying more economical and efficient muscular control 0 0. This reduced muscular burden likely contributes to higher control precision and flight stability, which aligns with objective flight performance metrics. These mixed physiological patterns indicate that more accurate control and self-reported performance do not necessarily coincide with uniformly lower physiological activation. These inconsistencies may reflect more complex mechanisms underlying physiological responses or other dominant factors that affect them, warranting further research.

Taken together, these results provide compelling evidence for the existence of experience transfer effects from drone operation to eVTOL piloting. These effects manifest as lower physiological arousal, reduced muscular effort, and better task performance. Cognitively, this transfer reflects shared mental models and stimulus–response mappings between drone and eVTOL joystick basic operations. However, transfer does not equate to full adaptation, and future studies should consider customized training to address the needs of different user groups and evaluate more advanced eVTOL flight skills, such as situation awareness and decision-making.

5.3 Limitations and future applications

This study has several methodological and technical limitations. First, although we used an MR-based 6-DOF flight simulator to create the experimental scenarios, it still eliminated real-flight risks and could not fully replicate complex traffic and weather, such as air turbulence. Thus,

participants' behaviors may still be biased to some extent. Future experiments in real eVTOL aircraft may be needed to verify our findings. Furthermore, constrained by resources, we were not able to further evaluate the heterogeneity of the participants, e.g., the existence of professional flying experience (e.g., on fixed-wing aircraft or helicopters) and the personality traits, which were important considerations in aviation 0 0. Future research with a larger sample size is needed. Next, we evaluated only planar trajectory deviation and did not account for altitude control, assuming the eVTOL control system would manage air turbulence and that altitude would remain constant along the target path. Future research may explore pilots' capability in following 3D trajectories in more complex scenarios. In addition, the training program only focused on operational tasks. Future training programs may emphasize more advanced tactical skills, which may be more critical to flight safety 0, and should measure cognitive skills such as situation awareness and decision-making alongside operational metrics.

Finally, the temporal dimension of training warrants further investigation. Although the present study demonstrated immediate improvements in basic control performance, performance gains within a training session do not necessarily establish long-term learning or retention (Soderstrom & Bjork, 2015). Research on procedural skills indicates that retention depends on the interval without practice, task characteristics, and opportunities for intermittent practice (Tatel & Ackerman, 2025). Because our post-training assessment occurred within the same experimental session, whether these improvements persist after one day, one week, or one month remains to be examined. Future studies should include delayed assessments before any additional practice to distinguish retained skills from relearning. Such evidence would extend the present findings on initial adaptation and help determine appropriate refresher-training intervals for introductory eVTOL operation.

6. Conclusions

In an MR-based 6-DOF eVTOL simulator, we explored, for the first time, the effect of short-term training on participants' performance in operating an eVTOL aircraft with a novel single-hand joystick control interface ready for real-world use. Supporting our hypotheses, our study validated the positive effect of short-term training on participants' basic eVTOL operational performance, which was further supported by participants' physiological and subjective responses. Further, we found that although drone pilots had no prior experience with eVTOL aircraft, their background in drone operation led to better performance in operating eVTOLs. To the best of our knowledge, this is the first time we have evaluated a commercially ready single-hand joystick control interface, and our findings highlight the critical role of operator background and skill-transfer mechanisms. By linking control performance to cognitive workload, arousal, and skill transfer, the study positions simplified eVTOL operation as a problem of human cognition—how novices acquire, automate, and transfer control skills—rather than merely of interface ergonomics. These results provide insights for the design of novel eVTOL control systems for the general public and underscore the need for adaptive basic operation training programs tailored for potential eVTOL users.

CRediT Authorship Contribution Statement

Yanbin Yang: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. Lei Lei: Writing – original draft, Methodology, Investigation, Conceptualization. Haiyu Li: Investigation, Formal analysis, Data curation, Conceptualization. Dubo Huang: Supervision, Resources, Project administration. Dengbo He: Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

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Declaration of Competing Interest

The author declares no competing financial interests or personal relationships that could have influenced the work reported in this paper. This research was conducted as part of the author's academic requirements for the MPhil program at the Hong Kong University of Science and Technology (Guangzhou), with no external commercial funding that might constitute a potential conflict of interest. All data collection and analysis procedures were conducted in accordance with relevant ethical guidelines.

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