Keeping Pilots in the Zone: Evaluating Adaptive Simulation-Based Flight Training

Carlie Swords, Maureen Namukasa, Meredith Carroll
Florida Institute of Technology
Melbourne, Florida
cswords2021@my.fit.edu, mnamukasa2020@my.fit.edu, mcarroll@fit.edu

Wendi L. VanBuskirk, Bradford L. Schroeder, Matthew D. Marraffino
Naval Air Warfare Center Training Systems Division
Orlando, Florida
wendi.l.vanbuskirk.civ@us.navy.mil, bradford.l.schroeder.civ@us.navy.mil, matthew.d.marraffino.civ@us.navy.mil

ABSTRACT

In aviation training, there is a need to reduce the large cost and time barriers for pilots to reach proficiency. By focusing on an individualized approach to training, pilots may be better kept in the Zone of Proximal Development, an area of optimal learning wherein learners are adequately challenged yet not overwhelmed, by moderating mental effort and stress, allowing for greater performance. Adaptive training (AT), which adjusts training based on various assessments of the learner's strengths and weaknesses, is one training methodology that can potentially accomplish these goals, having shown to improve learning gains, learner experience, and training speed in military and general learning domains (Fraulini et al., 2024). There is currently limited research evaluating the effectiveness of difficulty-based AT techniques in simulated flight training contexts. In our previous effort, findings revealed that adapting the difficulty of training based on performance and/or cognitive state for simulated flight applications can help moderate trainee mental effort as they accomplish the same training performance outcomes as the traditional training methodology; however, study limitations such as limited sample size, a larger-than-anticipated experience base, and ceiling effects appeared to have prevented this from translating into significant differences in learning gains (Swords et al., 2025). This experiment re-evaluated the use of adaptive difficulty based on performance, and adapting difficulty based on performance and individual difference ratings of mental effort, compared to a non-adaptive control, in a simulated flight training task, and found that adapting difficulty based on both performance and mental effort moderated mental effort, leading to greater training performance improvements. This paper presents the methods and results and discusses the theoretical and practical implications for aviation training in both civilian and military contexts.

ABOUT THE AUTHORS

Carlie Swords is an undergraduate Aeronautical Science with Flight student at Florida Institute of Technology's College of Aeronautics. She is a research assistant at the Advancing Technology-interaction and Learning in Aviation Systems (ATLAS) Lab, with a focus on aviation training systems.

Maureen Namukasa is a doctoral candidate and graduate research assistant at Florida Institute of Technology's College of Aeronautics. She has a bachelor's degree in industrial and organizational psychology and M.S. in Aviation Human Factors. She leads the ATLAS Lab research team, and her research interests include human performance analysis, urban/advanced air mobility, automation, human-centered design, UX and usability, interface and interaction design, and training design, development, and evaluation.

Dr. Wendi L. VanBuskirk is a NAVAIR Fellow and Senior Research Psychologist with the Naval Air Warfare Center Training Systems Division (NAWCTSD). During her 25-year tenure, she has led research programs at the Basic Research (BA-1) through Advanced Development (BA-4) to develop empirically sound instructional strategies, methods, and systems which provide effective training solutions for aviation, surface, sub-surface, and Marine Corps communities.

Dr. Bradford L. Schroeder is a Senior Research Psychologist at the Naval Air Warfare Center Training Systems Division (NAWCTSD). His research programs involve the development and evaluation of adaptive training algorithms and advanced technologies (such as Augmented Reality) to improve training effectiveness for complex

Navy-relevant tasks. In addition, his research investigates how individual differences in stress responses, cognitive abilities, and other learner characteristics can affect learning outcomes.

Dr. Matthew D. Marraffino is a NAWCAD Associate Fellow and Senior Research Psychologist with the Naval Air Warfare Center Training Systems Division (NAWCTSD). He has spent over a decade advancing the design and evaluation of training systems to improve warfighter readiness. His work integrates cognitive theories like Cognitive Load Theory and Cognitive Theory of Multimedia Learning into cutting-edge simulation-based training solutions for the Navy and Marine Corps.

Dr. Meredith Carroll is a Professor of Aviation Human Factors and Founder and Director of the Advancing Technology-interaction and Learning in Aviation Systems (ATLAS) Lab at Florida Institute of Technology's College of Aeronautics. She has over 20 years of experience studying human/team performance and training in complex systems, focused on decision making in complex systems, cognition and learning, human-autonomy teaming, performance assessment and adaptive training.

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INTRODUCTION

Time and resource barriers present challenges to the progression of aviators in training. Optimizing the approach to training would reduce the effect of these challenges and increase the rate at which pilots progress through the acquisition of crucial flight skills. There is research to suggest that this could be achieved by keeping the trainee engaged in the Zone of Proximal Development (ZPD), or the space between independent ability and potential development through guided instruction (Vygotsky, 1978). This style of customized training can be accomplished through adaptive training (AT), which adjusts the training to the strengths and weaknesses of the learner (Fraulini et al., 2024). AT has been utilized effectively to increase learning outcomes by employing a variety of techniques, including adaptations to content difficulty based on learner performance and mental effort (Salden et al., 2004). Previous research suggests that adapting training difficulty based on performance moderates pilot mental effort in simulated training tasks, allowing them to reach the same performance thresholds as traditional training strategies without overwhelm (Swords et al., 2025). However, there is little research that identifies the most optimal adaptation strategy for increasing training performance improvements for simulated aviation tasks. The current research examined the effect of two adaptive training techniques for flight training, including adapting difficulty based on a) performance only, and b) performance and mental effort, compared to a nonadaptive control, that incrementally increased difficulty throughout training. The following sections present the concepts of ZPD and adaptive training in learning applications, the methods used to assess the adaptive training strategies, and the results of the study.

LITERATURE REVIEW

Zone of Proximal Development (ZPD)

The identification and maintenance of optimal growth through the acquisition of new skills has been traced back to Vygotsky's fundamental sociocultural theory of a ZPD. Vygotsky describes this critical early learning area as, "the distance between the actual developmental level as determined by independent problem solving and the level of potential development as determined through problem-solving under adult guidance or in collaboration with more adept peers" (Vygotsky, 1978, p. 86). ZPD is achieved by balancing the challenge level experienced during learning with the abilities of the learner, such that they are challenged enough to avoid boredom but not challenged beyond their abilities to a point where frustration occurs (see Figure 1; Ackerman, 2025). Prior research suggests differences in the learning process between learners within the ZPD and those outside of it, with the maintenance of the ZPD leading to learning benefits. Kim and Han (2022) studied the effect of ZPD progression on interest and learning attitudes for 40 adult students and found that the use of frequent instructor scaffolding and discussion with peers to keep learners in their ZPD led to significantly higher interest and positive learning attitudes compared to a control group. Baker et al. (2020) analyzed Mathematics and English language performance for 7,913 elementary and middle schoolers in an online learning platform that assessed student performance to suggest applicable learning content to center learners in their ZPD. The program allowed instructors to assign either: Already-Mastered tasks (above the ZPD; "too hard"), Ready-to-Learn tasks (within the ZPD), or Unready-to-Learn tasks (below the ZPD; "too easy"). Students mastered significantly more skills when completing tasks designed for their ZPD than tasks outside of it (Baker et al., 2020). Similarly, utilizing the ZPD theory in training delivery has been used to increase the retention of complex learning content for language learning (Jama, 2024). This research provides evidence that maintaining learners in their ZPD can lead to greater learning outcomes.

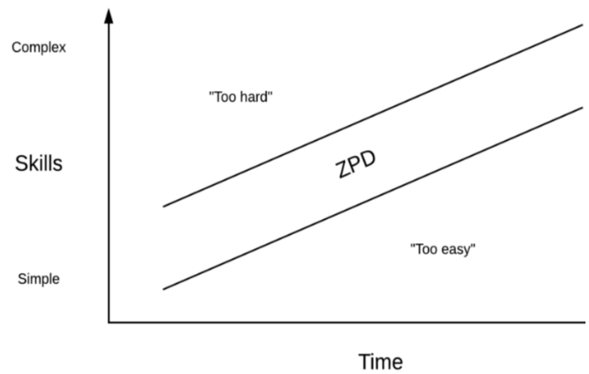

Figure 1. Vygotsky's ZPD Theory
Note. Ackerman, 2025.

The nature of ZPD is individualized and subjective for each learner; existing skill level and independent needs of learners affect the location of the learner in their own ZPD, and the location and size of the constructed ZPD changes based on learner skill level and the context of the training (Kim & Han, 2022). To effectively maintain a learner in their ZPD, the learner's individual skill level must be assessed to manipulate training content appropriately. The assessment of mastery in training can be measured by various items, including retention of information, academic grades, evaluations of knowledge depth and performance (Jama, 2024; Kim & Han, 2022).

Due to the ambiguity in defining exactly where the ZPD is for each individual learner, past research has focused on dynamic assessment tools that consider both the position of the learner and their likely potential (Mirzaei et al., 2017). Once the learner's ZPD has been identified, maintaining the learner in their ZPD involves the manipulation of instruction to keep learners engaged, but not overwhelmed. This type of content scaffolding is often done in the classroom environment by providing or removing educational aid to students based on their location in the development of learning (Yusuk, 2018). Yusuk (2018) investigated the effect of scaffolding techniques in ZPD maintenance for 48 university students in an English course. The instructor used 15 scaffolding techniques identified to maintain learners in their ZPD, such as guided prompting, use of visual aids, and peer assistance. The students were administered a reading comprehension pre- and post-test and a questionnaire regarding their attitudes toward the scaffolding techniques used. The test scores revealed that students' comprehension improved from pre- to post-course, and the questionnaire revealed that almost all techniques received high levels of approval (Yusuk, 2018). Similarly, Mirzaei et al. (2017) utilized collaborative group-dynamic feedback as a tool for maintaining ZPD for high school students in a language course. The students were divided into two groups: a group-dynamic feedback condition, for which collaborative dialog and feedback type were tailored between hints and prompts to direct feedback, and a non-dynamic feedback condition, for which feedback was direct and focused on correcting incorrect answers. Students completed two vocabulary assessment quizzes before and after completing the learning sessions. After eight sessions, the group-dynamic feedback condition was revealed to have maintained students in their ZPD, allowing them to display deeper vocabulary knowledge than the non-dynamic group. These studies provide evidence that there is a range of strategies that can keep learners in their ZPD leading to enhanced learning outcomes.

Adaptive Training to Maintain ZPD

One technique that has been used to maintain learners in their ZPD is adapting difficulty based on learner performance, an AT technique aimed at individualizing training based on the learner's strengths and weaknesses (Fraulini et al., 2024). The AT model can serve to ultimately keep learners within their individual ZPD by adjusting training to match a learner's level of expertise. Students who demonstrate mastery-level performance in a skill may not be challenged enough by their training, while learners who demonstrate poor performance may be training at a level too difficult for their current skillset. Adapting the difficulty of training has been found to lead to improved learning outcomes when compared to traditional training approaches. Ferguson et al. (2022) evaluated the effectiveness of such an approach in a virtual reality training context in which 40 learners were divided into either a non-adaptive condition, in which the difficulty of the in-game tasks remained the same throughout the 30-minute session, or an adaptive-condition, in which the difficulty level of tasks was adapted based on performance. Both cognitive load, assessed via the NASA-Task Load Index (NASA TLX), and a post-study knowledge test revealed that the adaptive difficulty condition led to lower cognitive load and higher transfer knowledge retention. These findings suggest that the adaptive difficulty technique kept cognitive load low, keeping learners in their ZPD, allowing for additional transfer of knowledge. Van Buskirk and colleagues (2019) developed an AT system for submarine electronic warfare officers utilizing ZPD theory as the basis for instantiating adaptive difficulty algorithms. They performed a training effectiveness evaluation with submariners that showed large performance improvements across several Submarine Learning Center sites. Further, a meta-analysis conducted by Wickens et al. (2013) showed that adapting training difficulty based on learner performance produces higher learning gains compared to changing difficulty at fixed schedules. This research provides evidence that AT may be an effective means of maintaining learners in their ZPD.

A key challenge with adapting difficulty to maintain learners' ZPD, is the determination of what measures to assess and how to adapt difficulty based on these measures. A variety of metrics have been used in the literature to achieve this, including both performance and cognitive measures, as well as combinations of the two (Obergassel et al., 2025; Salden et al. 2004). Performance has been measured in many ways, including errors from established standards and time to complete tasks. However, performance alone may not serve as a precise indicator of whether the learner is in ZPD as a learner could be performing well, but overwhelmed with limited cognitive resources available for learning, or with very little effort, resulting in boredom and lack of engagement or learning progress. Affective and cognitive measures such as stress and cognitive workload have been utilized as a basis to adapt training (Obergassel et al. 2015; Sahar et al. 2022) and may provide the additional granularity needed to assess where learners are with respect to their ZPD. There is theoretical and empirical support for the use of cognitive measures such as workload, also referred to as mental effort, and affective measures such as stress to adapt training.

Mental Effort as a Measure of ZPD

Mental effort can be used as a measure on which to adapt training and keep learners in ZPD. Mental effort is defined as the "…cognitive capacity that is actually allocated to accommodate the demands imposed by the task" (Paas et al. (2003, p. 64). Mental effort must be balanced to achieve optimal performance; a moderate amount of mental effort is needed to engage the learner, but an excessive mental effort might produce overload and costs to performance (Liu et al., 2025; Salden et al., 2004). Mental effort plays a critical role in training, as a learner must have adequate cognitive resources to allocate to actual learning while performing training tasks. Paas et al. (2005) suggest that both the actual mental effort expenditure and the perceived mental effort requirements for a task impact both performance and motivation. A high mental effort cost, or a perceived high cost, can reduce motivation for a task and thus affect the allocation of cognitive resources, impacting performance. However, students who elect to allocate increased mental effort to a task tend to perform better on learning indicators (Paas et al., 2005). Adapting training complexity around this relationship has led to beneficial learning impacts by moderating cognitive load to support learners (Obergassell et al., 2025). VanGog et al. (2020) found that the assessment of mental effort to self-monitor academic progress and the need for assistance or studying during learning tasks improved self-regulation and subsequent learning outcomes, such as performance. Additionally, greater application of mental effort to problem-solving tasks has been linked to greater academic performance and learning motivation (Liu et al., 2025). Thus, the moderation of mental effort in learning can aid in positioning a learner within their ZPD, ensuring adequate mental capacity to allow for the acquisition of skills without cognitive overwhelm.

Various measures have been used to assess mental effort, or workload, during learning, including heart rate variability, motivation, and self-report measures (Le et al., 2018; Liu et al., 2025; Obergassell et al., 2022; Salden et al., 2004). Swords et al. (2025) used cognitive assessments to adapt difficulty revealing that this moderated the mental effort of the learner as they achieved the same performance standards as traditional training provides. Pilots were tasked with completing simulated flight training that was either, a) non-adaptive, b) performance-adapted, or c) both performance-and-mental-effort-adapted. Mental effort and performance analyses from pre- to post-training revealed that the adaptive conditions moderated mental effort without sacrificing performance gains. However, this study was limited by ceiling effects and a confound of experience, which had a significant influence on the effect of the difficulty adaptations. Conclusive research on the performance impacts of adaptive techniques that utilize mental effort in conjunction with performance to adapt the training difficulty is limited, particularly in a flight training context.

Stress Coping as Measure of ZPD

Stress coping can also be used as a measure on which to adapt training and keep learners in ZPD. Stress has a unique effect on task performance; an inverted-U curve has been observed, suggesting that as stress increases, performance improves to a point; however, after reaching a peak stress level, performance begins to decline (Anderson, 1976). As such, a certain level of stress can be beneficial. In scenarios perceived as stressful, automatic responses to anxiety-inducting stimuli serve to increase performance effectiveness; however, only to a point, after which overload can occur, and performance suffers (Anderson, 1976). There is extensive research into the negative effects of stress on the "back-side" of the inverted-U curve. Heissell et al. (2021) conducted a study on 93 adolescent students to determine the effects of stress (measured as cortisol in saliva) on test performance. The results revealed that the students produced more cortisol in high stress test scenarios, and that students with identified chronic stress produced more cortisol, a steroid produced by the adrenal glands, than those without. Larger changes in cortisol levels led to poorer test performance, suggesting that stress in high amounts has negative effects on learning performance. These findings are consistent with other academic-based studies which have looked at stress impacts on academics over longer courses of time. Oketch-Oboth and Okunya (2018) administered a cross-sectional survey assessing perceived stress, Locus of Control, stress coping, and academic transcripts of 584 university students in Nairobi. The findings revealed a significant association, with higher stress leading to lower academic performance. Learners' responses to stress, and their use of stress-coping strategies, differ and may be in indication that a learner is not within ZPD, providing an opportunity to adapt training. Sahar et al. (2022) evaluated the use of stress measures to adapt the difficulty of training in a simulated game in which participants were assigned to one of three conditions: constant difficulty, constantly increasing difficulty, and adaptive difficulty based on stress. Participants in the third condition used a pressure-sensing joystick to complete a series of in-game tasks, for which the difficulty was adapted based on stress response. Greater pressure on the joystick indicated greater stress. The adaptive condition led to fewer performance errors and faster completion time than both of the non-adaptive conditions, suggesting the stress-based AT kept participants better positioned in their ZPDs. These studies suggest that learners stress responses may be indicative of when learners are outside of their ZPD.

The type of stress coping strategy used during learning can predict and moderate the effects of stress in some situations (Keech et al., 2018). One measure of interest for identifying stress coping strategies, the Coping Inventory for Task Stressors (CITS) developed by Matthews and Campbell (1998), indicates three main types of both dispositional and state stress responses: (a) task-focus (i.e., a tendency to seek out solutions to the stressor; TFC), (b) emotion-focus (i.e., a tendency to respond with self-criticism or worry to the stressor; EFC), and (c) avoidance (i.e., a tendency to direct focus away from the stressor; AC; Matthews & Campbell, 1998), with measures available to assess current stress-coping states and general dispositions. Task-focus coping is associated with increased effort and has been found to be most beneficial for high-stress learning (Matthews & Campbell, 1998). The state of emotion-focused stress coping has been found to correlate with higher workload, frustration, and higher mental demands (Matthews & Campbell, 1998). Matthews and Campbell (1998) found that, with regard to personality and coping strategy, task-focus was related to self-efficacy, emotion-focus was related to neuroticism and anxiety, and avoidance was related to low agreeableness and low conscientiousness. Schroeder et al. (2024) examined the relationship between coping strategies and performance on a complex military electronic warfare task. These authors found that higher TFC was associated with higher performance while higher EFC was associated with poorer performance. Further, these authors argued that stress-coping, particularly EFC, could be a valuable individual difference variable to integrate into the research and design of AT systems.

To summarize, adaptive difficulty has been shown to be effective in several different complex military tasks such as electronic warfare (Van Buskirk et. al., 2019), close air support (Marraffino et al. al., 2019), and submarine periscope operators (Landsberg et. al., 2012). However, when considering how to keep trainees in their ZPD, there are several individual difference measures that may affect how one moves in and out of their zone that could positively or negatively affect performance. Therefore, AT designers may benefit from the implementation of a hybrid adaptation approach in which an aptitude treatment interaction (ATI) approach combined with adaptive difficulty is the basis of adaptation decisions (Park & Lee, 2003).

CURRENT STUDY

Methods

To address the gaps in the literature, the current study aimed to examine methods for keeping novice pilots in the ZPD during simulated flight training by examining the impact of two adaptive-difficulty training methods on mental effort, stress-coping, and performance: (a) adapting difficulty based on performance alone, and (b) adapting difficulty based on performance and mental effort. Participants were tasked with completing eight simulated Instrument Landing System (ILS) approaches at various difficulty levels based on wind speed, wind gusts, turbulence, and visibility. During the training, the difficulty either increased incrementally or was adapted based on performance only or both performance and mental effort. The study was guided by four research questions. How do training methods that adapt difficulty based on performance only, or performance and mental effort, or incrementally increase difficulty, influence learner: (1) mental effort, (2) stress coping, (3) training performance; and (4) do individual difference stress-coping factors impact the effectiveness of adaptive training methods? It was hypothesized that by increasing the granularity of assessment by adapting training based on mental effort in addition to performance, learners would (1) experience more moderate levels of mental effort and (2) stress, and (3) greater training performance improvements. It was also hypothesized that individual differences in stress-coping dispositions might influence the training outcomes (4). The study was approved by the Naval Air Warfare Center Training Systems Division institutional review board.

Participants
Thirty-three participants were recruited from a Part 141 collegiate flight training program in the southeastern United States. Participants were required to be at least 18 years of age, and either currently enrolled in instrument flight training or have received their instrument rating within the past year; individuals with a Certified Flight Instructor or Airline Transport Pilot certificate were ineligible to participate. Participants were compensated with their choice of either a $50 gift card or extra credit in an academic course. Four participants' data were removed due to being outliers, or having a perfect score on the pre-test (i.e., no opportunity for training performance improvements). The final data set consisted of 29 participants, including 23 males and six females, with an average age of 22.4, (*SD* = 6.85), and average flight hours of 198.34 (*SD* = 56.29). Twelve participants held their Private Pilot's License (PPL) with Instrument Rating, 14 held their PPL without an Instrument Rating, and three held their Commercial Pilot's License.

Experimental Design and Task
The study utilized a 3x2 mixed experimental design. The between-subjects independent variable was the type of assessment method used for adapting training difficulty: Control (difficulty level was incrementally increased), Performance Only (difficulty level was adapted based on participant performance only; PO), and Performance and Mental Effort (difficulty level was adapted based on participant performance and mental effort; P+ME). Trial was the within-subjects variable with participants completing pre- and post-training assessments. Participants completed eight ILS approach scenarios in a simulated environment: a pre-training assessment scenario, six training scenarios, and a post-training assessment scenario. Participants began each scenario at 1600 feet altitude, three miles from the runway, and continued the approach until the participants notified the observer the runway was in sight, or had descended to 300 feet altitude, at which point the scenario ended. Nine difficulty levels, established with input from expert instructors, were used. The lowest difficulty level (1) included visual meteorological conditions (VMC; i.e., permitting flight with visual references outside of the aircraft), with no wind and no turbulence. The scenarios increased in difficulty by incorporating instrument meteorological conditions (IMC; requiring flight with sole reference to aircraft instruments) and various levels of crosswind, gusts, and turbulence, with the most difficult level (9) including a 20-knot crosswind, 20 knots of wind gusts, and mild turbulence in IMC conditions (see Table 1).

Table 1. Difficulty Levels

Level	1	2	3	4	5	6	7	8	9
Visibility	VMC	IMC	IMC	IMC	IMC	IMC	IMC	IMC	IMC
Crosswind*	0	0	10	10	15	15	15	20	20
Gust Factor*	0	0	0	5	5	10	10	15	20
Turbulence	None	None	None	None	None	None	Mild	Mild	Mild

Note. VMC = Visual Meteorological Conditions. IMC = Instrument Meteorological Conditions. * = Wind in knots.

The first approach was a pre-training test scenario at a moderate difficulty level (level 6; see Table 1). Participants then completed six ILS approach training trials, beginning at difficulty level 3, with the difficulty levels of the subsequent training scenarios being adapted based on their condition. For the Control condition, participants completed difficulty levels 3 through 8 sequentially, regardless of performance or mental effort experienced. Performance was assessed using errors or deviations from modified Federal Aviation Administration (FAA) standards for instrument approaches. An error was identified when: a) a deviation from target airspeed greater than 10 knots, or b) greater than a half-scale deflection on the localizer or the glideslope indicators. For the PO condition, the difficulty level was adapted based on the participant's performance on the ILS approach. If the participant had zero errors, they would move up two difficulty levels. Two or more errors required the participant to repeat the difficulty level. On the second attempt, the participant would move up one level if they had zero errors. The participant would move down one level if they had one error, and they would move down two levels if they had two or greater errors (see Table 2). For the P+ME condition, the difficulty level was adapted based on both performance errors and self-reported mental effort on a five-point scale, wherein a score of one reflected "very low mental effort," and five meant "very high mental effort." If participants scored zero errors and a mental effort rating equal to or less than three, they would move up two levels. If the participant scored greater than two errors and a mental effort rating of five, they would move down two levels (see Table 3). After completing six training trials, participants in all three conditions completed a post-test scenario at difficulty level 6.

Table 2. Performance Only Adaptation Matrix

Number of Errors	0 Errors	1 Error	2 or More Errors
First trial at a specified difficulty level	Move up 2 levels	Move up 1 level	Repeat
Second trial at a specified difficulty level (i.e., if level is repeated)	Move up 1 level	Move up 1 level	Move down 1 level

Table 3. Performance and Mental Effort Adaptation Table

Number of Errors	0 Errors	1 Error	2 or More Errors
1-3 Mental Effort	Move up 2 levels	Move up 1 level	Repeat
4 Mental Effort	Move up 1 level	Repeat	Move down 1 level
5 Mental Effort	Repeat level	Move down 1 level	Move down 2 levels

Experimental Setup

This study used a computer-based Honeycomb Aeronautical Simulator running X-Plane 12 software. The simulator featured a curved monitor for an out-of-the-window view of the aircraft, a yoke, and rudder pedals. Additionally, a Primary Flight Display (PFD) and a Multifunctional Flight Display (MFD) were positioned under the monitor using the Garmin G1000 panels, which were familiar to the sample. The PFD displayed the ILS glideslope and localizer indications, airspeed, heading, course, and attitude indicators. The MFD displayed engine information, including RPM. The aircraft model used in X-Plane12 was a small Cessna 172, an aircraft similar to those used in the sample's flight training program. See Fig. 2.

Figure 2. Simulator Testbed

Measures

Mental Effort

Mental effort was assessed after each scenario using a one-item, five-point Likert-type scale, adapted from Paas et al. (2003). The experimenter asked the participant, "consider the task you've just completed with regard to other simulator training you've performed. On a scale of one to five, with one being 'very low mental effort,' two being 'low mental effort,' three being 'moderate mental effort,' four being 'high mental effort,' and five being 'very high mental effort,' rate the mental effort required to complete that task." The participants were then shown a graphical scale that depicted the rating and verbally self-reported their mental effort score. The mental effort item was previously found to correlate significantly with the NASA TLX for pre-/post-test training assessment (Swords et al., 2025).

Performance

Participants were tasked with maintaining localizer and glideslope accuracy and upholding 90 knots indicated airspeed. Errors included: (a) more than a half-scale deflection of either the glideslope or the localizer needles and (b) airspeed deviations greater than 10 knots (FAA, 2018). Performance was monitored and evaluated during each approach by an observer; each error was recorded on an Excel spreadsheet that summed the total errors per trial. For the adaptive conditions, the observation spreadsheet produced an adaptive instruction based on either the performance errors alone or the performance errors and the mental effort rating.

Stress Coping

Prior to completing the training, participants completed a pre-study survey that assessed their dispositional stress coping strategies using the Coping Inventory for Task Stressors-Dispositional (CITS-D) questionnaire (Matthews & Campbell, 1998). The CITS-D is a 21-item survey that assesses the typical likelihood of the individual to cope with stressors using three different techniques: task-focus, which is related to intentionally facing the challenge; emotion-focus, which is related to responses of self-criticism or worry; and avoidance, which is related to the intentional directing of attention away from the challenge (Matthews & Campbell, 1998). Each coping strategy pertained to a subscale consisting of seven active statements. For each statement, participants were to rate how much they typically use the described activity to deal with stressful situations on a scale from zero (not at all) to four (extremely). For each subscale, responses were summed to produce a total score for that coping strategy, with a higher score reflecting a higher likelihood of coping with stressors using the associated technique. Reliability coefficients for the CITS subscales range from .84 to .86 (Matthews & Campbell, 1998). After each training trial, participants were administered a modified version of the Coping Inventory for Task Stressors-State (CITS-S) questionnaire. The original survey features 21 items, assessing the task-dependent coping strategies used by the individual, to rate the task just completed, based on the same three techniques assessed in the CITS-D. In the modified questionnaire, the three primary statements for each strategy, identified by Matthews and Campbell (1998) as having the highest factor loadings per subscale, were taken, resulting in a shortened nine-item survey more optimal for the study's time limitations.

Demographics

A pre-study survey captured the demographic data of the sample to examine any influence that individual differences had on training. Demographic information, including biological sex (Male, Female, Prefer Not to Say), age, race, and English-language proficiency were self-reported by the participants. Additionally, three measurements were used to determine experience level: flight hours, certificate level, and simulator use frequency. Participants were asked to provide an estimate of their logged flight hours, select the most recent flight certificate they had acquired (i.e., private pilot's certificate, instrument rating, or commercial flight certificate), and rate how frequently they used both at-home, computer-based flight simulators, and certified, full-panel simulators.

Procedures

Prior to the start of the study, participants were briefed on the purpose of the study, the experimental task, their right to withdraw at any point, and their voluntary participation in the study. They were then asked to provide verbal consent to participate. Once consent was received, participants were administered a pre-study survey via Qualtrics survey platform, assessing their demographic information, experience level, and the CITS-D. Once completed, participants were shown a slideshow introducing them to the simulator controls and instrument panels, including the locations of relevant information such as the localizer and glideslope indications, engine RPM, and airspeed. Participants were then asked to fly a short, simulated approach flight in VMC to get comfortable using the simulator. The participants were asked to verify whether they were comfortable with the controls. Once the participants were familiar with the testbed, they completed a pre-test, six training trials, and a post-test scenario. During the training trials, participants' performance errors were noted by the observer. After each training trial, the one-item mental effort question was administered, and the difficulty levels of the subsequent trials were adapted based on the condition of the participants, per the previous descriptions. At the conclusion of the study, participants' compensation was arranged.

RESULTS

Preliminary Analyses

The data were analyzed using Statistical Package for Social Sciences (SPSS; V 30), and a final sample size of N=29 participants. Prior to analysis of the primary research questions, participants' difficulty-level progression through the six training trials were analyzed to observe differences in the difficulty experienced by the two adaptive conditions as compared to the control group. Figure 3 depicts the PO (left) and P+ME (right) group progression through the difficulty levels, indicating the PO group experienced greater variability in difficulty level earlier in training. This may indicate that, without accounting for mental effort, the PO adaptations moved the participants out of their ZPD.

Additionally, we examined the total difficulty level experienced per each condition to determine if, overall, the groups experienced differences in the total difficulty experienced during training. A one-way analysis of variance (ANOVA) with a between-subjects independent variable (IV) of condition and a dependent variable (DV) of total difficulty (i.e., the sum of the difficulty levels experienced across the six training trials) revealed no significant group differences between total difficulty experienced, $F(2,26) = .31$, $p = .73$, $\eta p2 = .02$, hence we did not detect significant differences in the difficulty experience among our groups.

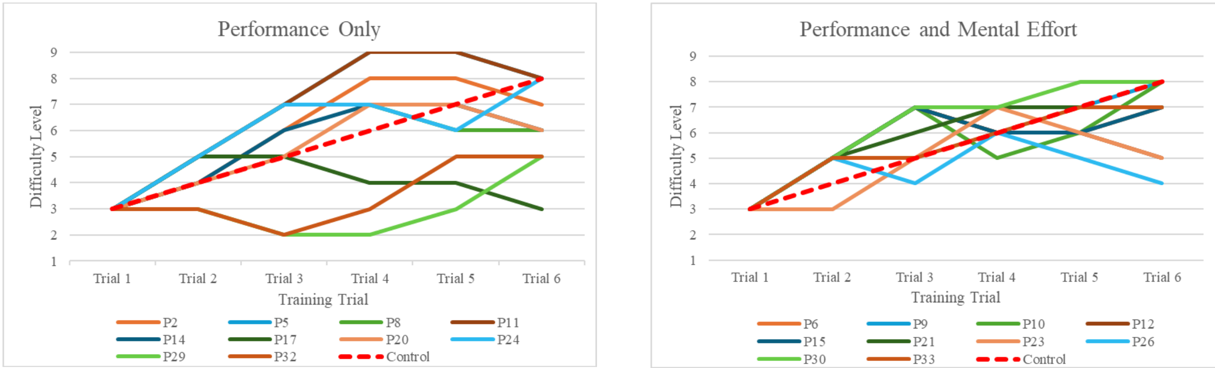

Figure 3. Difficulty Level Progressions for PO (left) and P+ME (right)

Primary Analyses

Mental Effort

To address Research Question 1, we examined the difference in the mental effort experienced throughout the six training trials based on condition. Figure 4 (left) reveals that the PO and P+ME groups experienced low to moderate levels of mental effort throughout the trials, while the Control group experienced high to very high levels of mental effort in the later trials. A repeated measures ANOVA with a within-subjects IV of training trial, a between-subjects IV of condition, and a DV of mental effort revealed a significant main effect of trial, $F(5,22) = 17.82$, $p < .001$, $\eta p2 = .80$, no significant main effect of condition, $F(2, 26) = 1.28$, $p = .30$, $\eta p2 = .09$, and a significant interaction between trial and condition, $F(10, 46) = 4.73$, $p < .001$, $\eta p2 = .507$. Post hoc results revealed differences in mental effort per condition and trial. In Trial 5, Control had significantly higher ME than P+ME ($p < .05$), and in Trial 6, Control had significantly higher ME than both Performance Only ($p < .005$) and P+ME ($p = .005$), suggesting the adaptive conditions served to moderate mental effort experienced in later trials, providing support for our first hypothesis.

Stress-coping State

To address Research Question 2, we examined the effect of condition on the stress-coping strategies (i.e., task-, emotion-, and avoidance-focus) employed by the participants during training (see Figure 4 (center)). Three mixed factorial ANOVAs were conducted, one for each coping strategy, with a within-subjects IV of training trial, a between-subjects IV of condition, and a DV of CITS-S score. For the task-focus coping strategy, there was a significant main effect of trial, $F(5,22) = 4.56$, $p = .005$, $\eta p2 = .51$. However, there was no significant main effect of condition, $F(2, 26) = .264$, $p = .77$, $\eta p2 = .02$ nor an interaction between trial and condition, $F(10,46) = 1.57$, $p = .146$, $\eta p2 = .26$. For the avoidance coping strategy, there was no significant main effect of trial, $F(6,21) = 1.62$, $p = .190$, $\eta p2 = .32$, nor of condition, $F(2, 26) = 2.36$, $p = .115$, $\eta p2 = .15$, and no significant interaction between trial and condition, $F(12,44) = 1.01$, $p = .459$, $\eta p2 = .215$. However, for the emotion-focus coping strategy, trial had a significant main effect, $F(6,21) = 3.15$, $p = .023$, $\eta p2 = .47$, there was no significant main effect of condition, $F(2, 26) = 2.98$, $p = .068$, $\eta p2 = .187$, and there was a significant interaction between trial and condition, $F(12,44) = 2.25$, $p = .025$, $\eta p2 = .38$, wherein during trial five, the control group reported significantly higher emotion-focus coping strategy scores than the PO group ($p<.05$) and the P+ME group ($p<.001$), and during trial six, the control group reported significantly higher emotion-focus coping strategy scores than the P+ME group ($p<.05$). This suggests that in the trials in which the control group experienced high or very high mental effort, they may have also had more difficulty effectively coping with stress than the adaptive conditions, providing support for our second hypothesis**.**

Training Performance

To address Research Question 3, we examined the effect of condition on pre- to post-training performance errors, by conducting a mixed factorial ANOVA with a within-subjects IV of training trial (pre and post), a between-subjects IV of condition, and a DV of performance errors (see Figure 4 (right)). There was a significant main effect of trial on pre- to post-test performance errors, $F(1,26) = 40.07$, $p < .001$, with performance errors decreasing from pre- to post-test across all groups. There was no significant main effect of condition, $F(2,26) = .29$, $p = .75$, $\eta p2 = .02$, but there was a significant interaction between trial and condition, $F(2,26) = 3.58$, $p = .04$, $\eta p2 = .22$, with the P+ME performing significantly better than PO and Control at posttest, providing support for our third hypothesis.

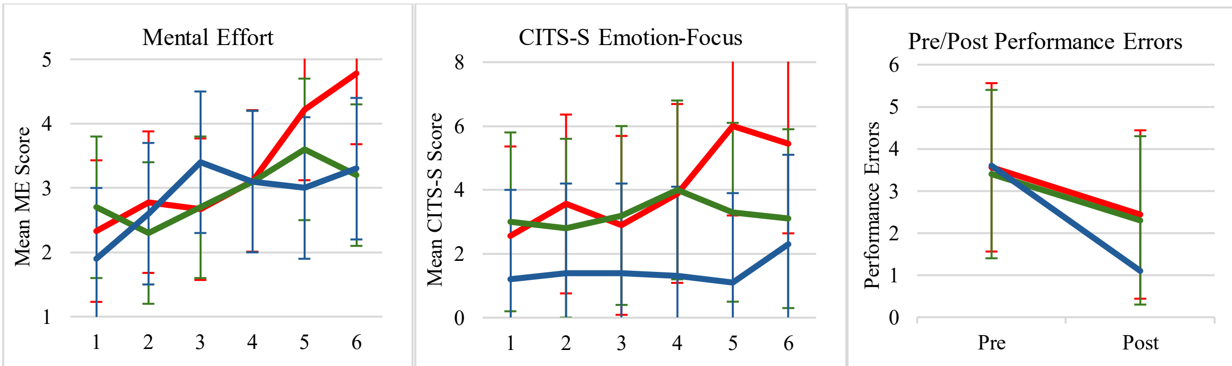

Figure 4. Mental Effort (left), CITS-S Emotion-Focus (center), Pre/Post Performance Errors (right) per Condition

Note. Legend: = Control; = Performance Only; = Performance and Mental Effort. Mental effort was rated on a scale from 1 (very low) to 5 (very high). CITS-S reflects the sum of three coping strategy usage statements rated from 0 (not at all) to 4 (extremely) for a total range from 0 to 12. Error bars reflect 95% Confidence Interval.

Stress-coping Disposition

To address Research Question 4, we examined the relationship between stress-coping disposition and pre- and post-test performance by conducting a Pearson correlation analysis between the pre- and post-test performance errors and the three CITS-D coping strategy scales. Neither emotion-focus (r = -.35, p>.05), nor avoidance coping (r = -.15, p>.05), dispositions were significantly correlated with pre-test performance. Emotion-focus (r = -.25, p>.05) and avoidance coping (r = -.10, p>.05), dispositions were also not significantly correlated with post-test performance. However, task-focus coping disposition was significantly and negatively correlated with both pre-test errors (r= -.503, p<.01), and post-test errors (r= -.527, p<.01). However, an ANCOVA with CITS-D task-focus as a covariate, a within-subjects IV of trial (pre and post), a between-subjects IV of condition, and a DV of performance errors revealed that CITS-D was not a significant covariate, $F(1,25) = .42$, $p = .52$, ηp2 = .02, indicating that participants' disposition towards certain stress coping strategies did not significantly influence training outcomes, failing to provide support for our fourth hypothesis.

DISCUSSION

Summary of Findings

This study evaluated two adaptive training strategies, one that adapted difficulty based on performance only and one that adapted difficulty based on both performance and mental effort, compared to a non-adaptive control that incrementally increased training difficulty. The type of adaptive strategy affected the participants' difficulty level progressions through the training scenarios. Participants in the PO group experienced both much higher and much lower difficulty earlier in training than the P+ME. We believe the combination of both performance and mental effort moderated difficulty level progression, more appropriately placing participants within the training challenge. Further, both adaptive strategies moderated the participants' mental effort ratings compared to the control, with the adaptive conditions remaining at moderate to low levels of mental effort, while the control experienced high to very high mental effort in the later trials. This may be due to some participants experiencing higher levels of difficulty than they were prepared for as the difficulty was increased incrementally, without consideration for their performance or mental state. Furthermore, the P+ME condition moderated participants' use of emotion-focus coping, which is often related to increased mental workload and frustration. We believe that the more precise adaptations based on the addition of mental effort allowed participants in the P+ME group to experience different stressors, and cope more effectively without overwhelm. Finally, the P+ME group had significantly greater training performance improvements from pre- to post-training than both the PO group and the Control, likely due to the reduced mental effort experienced and maintenance of participants in their ZPD. Additionally, individuals' task-focused stress-coping disposition was significantly correlated with both pre- and post-training performance, suggesting that, because the sample had prior skill in the task domain, some had developed effective stress-coping strategies to handle stressful flight conditions, which may have influenced performance. However, as revealed by the non-significant repeated-measures ANCOVA, the disposition did not significantly influence training performance improvements.

Theoretical Implications

Vygotsky's theory of ZPD indicates that meaningful learning occurs in an area between overwhelm and boredom, and that changes in instructional content should aim to keep the learner in this zone (Vygotsky, 1978). We believe that adapting training with the self-reported mental effort allowed learners to more accurately position themselves in the appropriate training context, whereas the PO adaptations may not have accounted for personal cognitive demands when performance was sufficient. These findings align with previous studies examining the effect of ZPD-centered learning on mental workload, wherein the students benefited from moderated cognitive loads and thus experienced greater performance improvements (Ferguson et al., 2022). This is also consistent with findings regarding the value of adaptive training based on cognitive measures, such as stress or cognitive load, which has been found to more appropriately administer training for significant performance improvements compared to adaptations based on performance alone (Obergassel, 2024; Sahar et al., 2018). Additionally, the use of emotion-focus coping strategies was different between the groups, suggesting the stressors experienced by the conditions may have differed. Emotion-focus coping has been found to correlate with anxiety, mental workload, and frustration (Matthews & Campbell, 1998). We found that as mental effort increased in the later trials for the control condition, this was accompanied by higher levels of emotion-focus stress coping. This may have potentially placed participants in the downward-side of the inverted-U stress curve, wherein performance diminishes with higher stress (Anderson, 1976). This aligns with scholars who suggest excessive stress negatively affects performance in academic contexts (Heissell et al., 2021; Oketch-Oboth & Okunya, 2018). The dispositional stress-coping strategies may have also had an impact on performance both before and after training, suggesting that tendencies to favor positive, task-focused stress-coping may reduce performance errors. This is in line with the findings of Matthews and Campbell (1998), which relate task-focus coping to greater effort, as well as Cheney et al. (2015), which suggest task-focus coping relates to resilience and high achievement. Differences in performance outcomes between the two adaptive conditions suggest that the addition of mental effort when evaluating training allowed for more adequate training delivery. Although participants' performance in the PO group may have indicated skill mastery, the intrinsic load associated with task performance may have been too high, minimizing the opportunity for germane cognitive processing required to learn. When mental effort was considered in the P+ME condition, cognitive capacity was evaluated, and participants were provided opportunities for further practice before advancing the difficulty if cognitive load was too high. This ZPD-centered approach has been used to improve learning outcomes in previous studies, increasing the learning gains, engagement, and performance of learners (Jama, 2024; Kim & Han, 2022; Mirzaei et al., 2017).

Practical Implications

The aim of identifying more efficient flight training strategies is to assist in overcoming training barriers, such as cost and time, while maintaining or improving training effectiveness. The findings of this study suggest that adaptive training based on both performance and mental effort may accomplish these goals by maintaining pilots in their ZPD. Adapting training difficulty based on trainee performance and mental effort may allow learners to reach higher performance thresholds faster than traditional training strategies that deliver a one-size-fits-all curriculum. The use of difficulty-based intervention styles for adaptive systems has been supported by previous research, but the findings of this study emphasize the utility of individual difference variables, such as mental effort, in improving training effectiveness. This combined approach to adaptive aviation training may reduce training cost and time and increase the output of skilled aviators. Additionally, this approach may moderate the mental effort of pilots in training, allowing for spare mental capacity to be applied toward other training concepts necessary to fly. This approach may also reduce stressors associated with high workload and anxiety, facilitating more efficient coping strategies. Flight training can be a source of stress, posing difficult, fast-paced curricula. Adapting to the mental effort of pilots in training may support learning in difficult contexts without stifling necessary performance accomplishments or accelerate skill mastery for aviators who might typically experience boredom from a less-than-optimal challenge. Adaptive training may be used to more effectively design and pace flight training, introducing appropriate material at the most optimal point in training to match learner skill level and mental workload. Further, fairly simple assessment techniques were utilized to assess performance errors and mental effort, and it is hypothesized that these types of measures could be easy to integrate into training at scale. A simple 1-item mental effort question could be integrated into an online survey, which could be combined with performance data from the simulator, and simple algorithms could determine the next difficulty level to present to the flight student.

Limitations and Future Research

This study has potential limitations that may affect the generalizability of the findings. First, a limited sample of only 29 participants was used. Additionally, due to time restrictions present in the study, only short training trials were conducted with six trials per participant, which may have restricted the adaptative movement of participants through the difficulty levels as well as their ability to train in more difficult scenarios. Due to the nature of sampling at a collegiate-level aviation program, the findings are generalizable to pilots with relatively low experience and may not reflect the training strategies used in more intense aviation training contexts. Future research should investigate the effects of adapting training difficulty based on performance and mental effort with a more experienced sample and more difficult training tasks to determine if these findings are replicable in different training contexts. Furthermore, adaptive training over the course of a longer timescale should be studied to determine suitability in typical flight training curricula.

CONCLUSION

This study evaluated the effect of two adaptive training strategies, compared to a nonadaptive control, on pilot performance, mental effort, and stress-coping for 29 collegiate-level flight training students. The results of the study indicated that adapting the difficulty of training based on both performance and mental effort might moderate mental effort and improve stress-coping, ultimately improving pilot performance outcomes in simulated training contexts. Further research should investigate the effect of performance and mental effort adaptive training on a more experienced sample with more difficulty training tasks to determine whether expertise level impacts the applications of adaptive training. Furthermore, adaptive training over the course of a longer timescale should be studied for flight training to determine suitability and feasibility in typical flight training curricula, including different types of flying environments.

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