Optimizing Simulation Fidelity for Cost-Effective Aviation Training

Mark Zais, Patricia Sowles, Frank Turinsky, Matthew Zepp
Integration Innovation, Inc.
Huntsville, Alabama
mark.zais@i3-corps.com, patricia.sowles@i3-corps.com,
francis.turinsky@i3-corps.com, james.zepp@i3-corps.com

ABSTRACT

This study, conducted on behalf of Program Executive Office (PEO) Aviation, assesses the effectiveness of various simulation fidelity levels for aviation training. Key findings challenge conventional assumptions about the role of motion cueing in simulation-based training. A comprehensive review suggests that for a range of training tasks, seat-based motion cueing may provide performance gains comparable to full-motion simulators, challenging the widely held assumption that more complex and costly motion systems are always necessary. This suggests potential cost-saving opportunities by employing more scalable seat-based solutions for specific training objectives.

We propose a framework for independently evaluating the effects of visual fidelity and motion fidelity on training transfer. This approach enables tailoring simulation capabilities to optimize training effectiveness and resource allocation across different training phases and environments. To determine the cost-effectiveness of simulation-based training, the study introduces the Transfer Effectiveness Ratio (TER) and Cost Effectiveness Ratio (CER) methods, which are further enhanced by incorporating a proficiency factor and developing a multi-stage model.

The findings emphasize the importance of a comprehensive data collection and analysis strategy, including defining requirements for capturing performance metrics from training devices, both in institutional settings and deployed operational units. An approach that aligns simulated and live training data streams enables closed-loop assessments of training impacts.

The study also explores additional considerations, such as the relationship between fidelity and experience levels, mission planning and databases, emerging technologies, deployed mode requirements, and accreditation standards. The findings provide a roadmap for developing more efficient, targeted, and adaptable training solutions across the aviation enterprise. Specific recommendations include implementing seat-based motion cueing for suitable task categories, adopting the fidelity evaluation framework to optimize simulation investments, and leveraging data-driven insights to continuously refine training programs.

ABOUT THE AUTHORS

Mark Zais, PhD is a Senior Technologist at Integration Innovation Inc. (i3). He joined i3 in 2022 and leads the Data and Analytics practice to support i3 portfolios and business units. Prior to his current role, Mark served in the military for 26 years before retiring as an Army Colonel. He spent the first part of his career in multiple assignments as a Longbow Apache (AH-64D) helicopter pilot before transitioning to the Operations Research military specialty. Mark has a degree in operations research from the United States Military Academy (West Point), master's degrees in operations research and industrial engineering from the Georgia Institute of Technology, and a Ph.D. in Business Administration (Operations Research) from the University of Colorado at Boulder.

Patricia Sowles is the Instructional Systems Designer (ISD) Director and ISD Branch Manager at i3. She is an Army veteran with a background in Military Training, Educational Technology, and Computer Science. Her visionary approach to instructional design seamlessly integrates cutting-edge methodologies with time-honored pedagogical principles, ensuring transformative learning experiences for i3's programs. Guided by the principles of servant leadership, Patricia fosters a culture of empowerment, collaboration, and innovation within i3's ISD branch, setting the standard for excellence in both military and civilian realms. Patricia's academic journey, including her ongoing

pursuit of a Doctor of Philosophy (PhD) in Advanced Educational Studies – Instructional Design and Technology from Liberty University, reflects her commitment to continuous learning and academic excellence.

Frank Turinsky, MSc is a Project Lead and AH-64 Subject Matter Expert at i3. He joined i3 in 2021 after retiring from the military. Frank's military aviation experience includes serving as a Crew Chief/ Flight Engineer in the CH-46E Sea Knight and KC-130F Hercules in the United States Marine Corps. He also served in the United States Army as an Instructor Pilot and Directorate of Evaluations and Standardization Maintenance Test Pilot Evaluator in the AH-64D/E. He retired from the Army as a Chief Warrant Officer 5 after 33 years of service and ten deployments worldwide. Frank holds a Bachelor of Science Degree in Professional Aeronautics as well as a Master of Science Degree in Management and Human Factors, both from Embry-Riddle Aeronautical University.

Matthew Zepp is the Director of Army Training Development at i3. He joined i3 in 2021 and leads the Army Training Development Organization within i3, supporting the Army customer with Virtual Training, Simulation, and Gaming products. Prior to his current role, Matthew has served the last 24 years in a variety of roles in the defense industry as an active-duty Army Officer- Aviator, a Department of the Army Civilian as a Sr. Training Specialist specializing in Flight Simulation, instruction, and maintenance management, and as a contractor specializing in Training Aids, Devices, Simulators, and Simulation. Matthew holds a BS in Aeronautics from Embry Riddle Aeronautical University and an MBA from the University of Alabama.

Optimizing Simulation Fidelity for Cost-Effective Army Aviation Training

Mark Zais, Patricia Sowles, Frank Turinsky, Matthew Zepp
Integration Innovation, Inc.
Huntsville, Alabama
mark.zais@i3-corps.com, patricia.sowles@i3-corps.com,
francis.turinsky@i3-corps.com, james.zepp@i3-corps.com

INTRODUCTION

The role of high-fidelity simulation in modern military aviation training is increasingly critical for ensuring operational readiness and effectiveness. This study, initiated by the U.S. Army's Program Executive Office (PEO) Aviation, aims to assess the effectiveness of various simulation fidelity levels for Army aviation training. It covers various echelons, ranging from institutional training setups to operational units deployed in the field. The research objectives are multifaceted, encompassing an examination of fidelity requirements for institutional versus operational training, the relationship between fidelity and operator experience levels, the efficacy of flight training devices for novice aviators, and the potential of emerging technologies such as virtual reality (VR) and augmented reality (AR) in meeting training needs. The study also explores the cost-effectiveness of simulation-based training and proposes a framework for independently evaluating the effects of visual fidelity and motion fidelity on training transfer.

To achieve these objectives, the study employed a comprehensive empirical methodology, including document reviews, expert interviews, and site visits. The research utilized a systematic approach, breaking down fidelity into physical, functional, and cognitive components, and employed a standardized 1-5 rating system for objective evaluation by subject-matter experts. A structured task analysis was conducted, leveraging the expertise of former Army aviators to evaluate and stratify fidelity requirements for specific training tasks outlined in relevant aircrew training manuals, such as the AH-64E Aircrew Training Manual.

The study introduces the Transfer Effectiveness Ratio (TER) and Cost Effectiveness Ratio (CER) methods to determine the cost-effectiveness of simulation-based training. These methods are further enhanced by incorporating a proficiency factor and developing a multi-stage model to account for the varying impact of simulation at different stages of a pilot's career. Additionally, the study emphasizes the importance of a comprehensive data collection and analysis strategy, including defining requirements for capturing performance metrics from training devices, both in institutional settings and deployed operational units. An approach that aligns simulated and live training data streams enables closed-loop assessments of training impacts.

This multi-pronged approach facilitated a nuanced understanding of how different fidelity levels impact training outcomes across physical, functional, and cognitive dimensions, while also considering cost-effectiveness and the role of data analytics in optimizing simulation-based training.

FIDELITY DIMENSION IN AVIATION SIMULATION

Fidelity is characterized by its relationship to the simulation training device, spanning physical, functional, and cognitive dimensions. As displayed in Figure 1, these dimensions are evaluated based on specific accreditation standards, typically using a rating scale from 1 to 5, where 1 indicates a high level of fidelity, and 5 indicates a low level of fidelity.

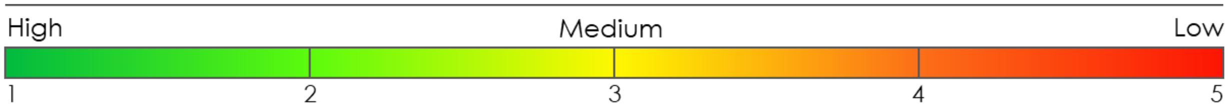

Figure 1. Simulation Fidelity Levels and Ratings

Certain tasks may be incompatible with simulation training due to the absence of specific aircraft components necessary for their execution. In such cases, the task is considered unsuitable for simulation, falling outside the 1 to 5 rating scale.

Physical Fidelity

Physical fidelity refers to the degree of replication required for a training device component in terms of physical characteristics, such as size, shape, weight, location, appearance, and movement. It can be further categorized into:

1. **Motion**: The extent to which a simulator replicates kinesthetic and vestibular feedback, including acceleration, deceleration, and spatial orientation. While some studies suggest limited need for full motion simulation in flight training devices, motion or vibration platforms have been shown to be useful for certain tasks that require minimal instructor prompting or motion cueing (Woody, et al., 2020) (Sparko & Bürki-Cohen, 2010) (Stanney, Hughes, Fidopiastis, & Jasper, 2021).

2. **Visual**: The level of realism in visual representations of the aircraft's external environment, spatial relationships, distances, scales, and environmental conditions. Visual fidelity is a powerful component, as trainees often prioritize visual cues over sensations when conflicted (Stanney, Hughes, Fidopiastis, & Jasper, 2021). It encompasses aspects such as out-the-window displays, observable degrees and angles, and the accuracy of visual representations.

3. **Tactile Sensation**: The accuracy in simulating the tactile sensations and feel of controls, feedback, and other physical interactions in the cockpit. Replicating the sense of touch and pressure experienced during helicopter flight through somatosensory stimuli can provide a higher level of fidelity in simulating sensory stimuli resulting from flight (Federal Aviaition Administration, 2023).

4. **Auditory**: The precision in replicating sounds within the aircraft and its environment, such as engine noise, auditory warnings, and other crucial aural cues. Auditory fidelity is essential for fully immersing pilots in the simulated environment, enabling them to grasp the cognitive load and retain the skills being practiced.

Functional Fidelity

Functional fidelity refers to the minimum required performance level of a training device component in relation to the actual aircraft component, displays, and systems in terms of rate, intensity, and interaction with other systems. Essentially, it is defined as the degree to which the simulator (or component) acts like the real equipment. Some research concludes that physical and functional fidelity both have a strong effect on performance and should not be dealt with in isolation (Myers, Starr, & Mullins, 2018).

Cognitive Fidelity

Cognitive fidelity is the ability of the simulator to replicate the cognitive skills required in the flight deck, including psychological and perceptive factors such as anxiety, stress, decision-making, and situational awareness. Cognitive abilities are directly related to the individual's perception of their performance and future performance. When immersion and presence are combined and applied appropriately, simulated training devices can provide satisfactory results for similar tasks trained in a non-simulated environment, as simulation training relies on synaptic additions that allow for information retention and enhanced recall in unrelated situations.

EFFECTIVENESS OF SEAT VIBRATION vs. FULL-MOTION SIMULATORS

A key finding from this research challenges the conventional wisdom that high-fidelity, full-motion simulators are essential for effective aviation training. The empirical review suggests that for many training tasks, seat-based motion cueing (vibration) can provide performance gains comparable to more expensive full-motion simulators. This finding is counter to the widely held assumption that higher complexity and costlier motion systems inherently yield better training outcomes.

Several factors support this observation; first, the physical limits of a full-motion simulator's motion base mean that the ratio of inertial cues to visual cues is not accurately replicated compared to actual flight conditions. Second, the research has not found empirical evidence to suggest a greater cost-benefit of using six degrees of freedom (6DOF) motion systems in lieu of more affordable seat shakers and vibration plates for many training tasks.

Furthermore, while full motion systems offer a more comprehensive range of movements, the trade-off lies in the level of realism required for specific training objectives. For tasks that do not necessitate highly complex maneuvers, vibration systems can provide adequate motion cues while being more cost-effective, requiring a smaller footprint, and offering portability.

These findings suggest potential cost-saving opportunities by employing more scalable seat-based motion cueing solutions for suitable training tasks, rather than investing in complex and expensive full-motion simulators across the board. Innovative solutions, such as using smaller, commercial off-the-shelf electrical servos in flight training devices (FTDs), can help achieve a high level of movement while reducing the footprint and cost challenges associated with traditional 6DOF devices, which require additional facilities to house the FFS.

Quantitative evidence from the study supports these findings. The research found that full motion is beneficial to less than 5 percent of training tasks (Stewart, Johnson, & Howse, 2008). Furthermore, the U.S. Army Attack community has successfully taught and trained all existing Aircrew Training Manual flight tasks in devices without full motion since the AH-64A Combat Motion Simulator (CMS).

FIDELITY AND MOTION INDEPENDENCE

Another significant insight from this study is the recognition that fidelity in training devices—encompassing physical, cognitive, and functional dimensions—can be optimized independently of motion capabilities. This finding indicates that effective training can be achieved without extensive motion systems, potentially reducing costs, and enabling investments to be focused on other critical aspects of simulation fidelity.

The analysis revealed that the relationship between fidelity and motion in a training device is not intrinsically interconnected. These elements can be assessed and fine-tuned separately to understand their individual impacts on training effectiveness. Evidence, however, suggests that increasing visual fidelity and aligning physical and functional fidelity contribute more to improved training than full motion. Moreover, seat vibration is deemed as sufficient as full motion in most surveyed flight training environments.

The study revealed that current motion technology cannot replicate actual motion cues in coordinated flight to a level of 100 percent (Myers, Starr, & Mullins, 2018). Substantial empirical evidence supports the effectiveness of flight simulation for training while virtually no evidence supports quantifiable training effectiveness of motion platforms (McCauley, 2006). This decoupling of fidelity and motion opens opportunities to tailor simulation capabilities more precisely to specific training objectives and environments, optimizing resource allocation and maximizing training effectiveness.

COST BENEFIT ANALYSIS

To determine the cost-effectiveness of simulation-based training, the study proposes using the Transfer Effectiveness Ratio (TER) and Cost Effectiveness Ratio (CER) methods (Stanney, Hughes, Fidopiastis, & Jasper, 2021). The TER measures the benefit of training in a simulated environment by comparing the performance of trainees who received simulation training to those who did not (Callendar, 2008). TER is calculated in Equation 1:

$$TER = (Y_0 - Y_x)/X_i \tag{1}$$

where Y_0 is the number of iterations required for the control group to meet a performance standard in the aircraft, Y_x is the number of iterations required for the experimental group to meet the same standard in the aircraft after receiving simulation training, and X_i is the number of iterations required for the experimental group to meet the standard in the simulator. The CER, in Equation 2, considers the relative costs of the aircraft and the specific simulation device:

$$CER_i = TER \cdot \theta_i \cdot \varphi_i \tag{2}$$

where $\theta_i = t_o / t_i$ is the ratio of the average time per iteration in the aircraft to the average time per iteration in the device type "i", and $\varphi_i = f_o / f_i$ is the ratio of the per-hour operating cost of the aircraft to the per-hour operating cost of the simulation device. Therefore, when the average time per iteration in simulation device type "i" is the same as in the aircraft ($\theta_i = 1$), the minimum TER required for positive cost-effectiveness is $TER > 1/\varphi_i$ (Callendar, 2008).

By calculating these ratios for each task and simulation device, training developers can determine which tasks are most cost-effective to train in a simulator and which simulation devices provide the greatest return on investment. This approach enables data-driven decision-making to optimize the allocation of training resources.

Enhancing TER and CER with a Proficiency Factor

To account for the potential impact of increased simulation on pilot proficiency, we propose modifying the Transfer Effectiveness Ratio (TER) formula by introducing a proficiency factor, denoted as α. This factor will adjust the TER based on the ratio of simulation to live flight hours, reflecting the potential decline in training effectiveness as the proportion of simulation hours increases beyond a certain threshold. The modified TER formula can be expressed as:

$$TER_\alpha = \alpha\,(Y_0 - Y_x)/X_i \tag{3}$$

where TER_α is the proficiency-adjusted TER and α is the proficiency factor (calculated based on the ratio of simulation to live flight hours.)

The proficiency factor, α, can be determined using a piecewise function, shown in Equation 4, that assigns different values based on the ratio of simulation to live flight hours, such that $\varphi_i = X_i / (X_i + Y_x)$.

$$\alpha = \begin{cases} 1, & \text{if } \varphi_i \leq 0.5 \\ 1 - (\varphi_i - 0.5)k, & \text{if } \varphi_i > 0.5 \end{cases} \tag{4}$$

In this example, the proficiency factor remains 1 (i.e., no adjustment) if the ratio of simulation hours to total training hours is less than or equal to 0.5. When the ratio exceeds 0.5, the proficiency factor decreases linearly based on the excess proportion of simulation hours, with the rate of decrease determined by the constant "k." The value of "k" can be derived from empirical data or subject matter expert input on the relationship between simulation ratio and proficiency outcomes. The proficiency adjusted TER_α can then be used to calculate the modified CER in Equation 5.

$$\mathrm{CER}_\alpha = \theta_i \varphi_i TER_\alpha \tag{5}$$

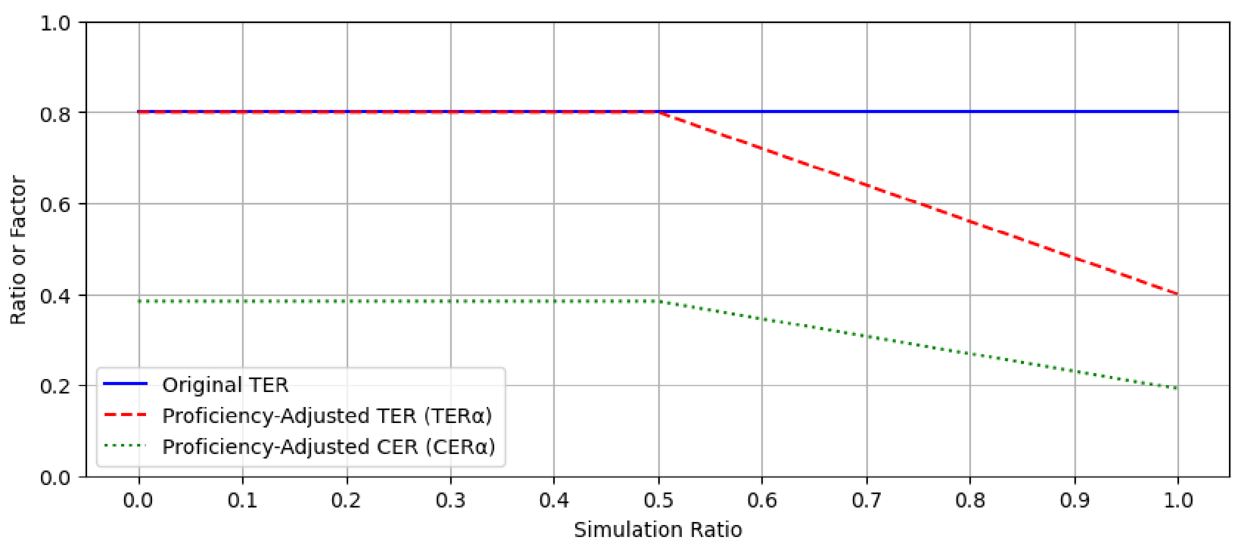

Figure 2. Proficiency-Adjusted TER and CER vs. Simulation Ratio

To visually represent the impact of the proficiency factor on the TER and CER, we can plot these values against the simulation ratio, as shown in Figure 2. This illustrative example, where a notional TER equals 0.8, demonstrates several key insights:

- The proficiency factor adjusts the TER and CER when the simulation ratio exceeds a threshold of 0.5. This adjustment reflects the potential decline in training effectiveness as the proportion of simulation hours increases.
- While the original TER remains constant, the proficiency-adjusted TER (TER_{α}) and proficiency-adjusted CER (CER_{α}) decline as the simulation ratio exceeds 0.5. This decline indicates a potential reduction in training effectiveness and cost efficiency as the use of simulation increases.
- The rate of decline in TER_{α} and CER_{α} is influenced by the constant k. A higher k value results in a steeper decline, indicating greater sensitivity to increased simulation hours. Conversely, a lower k value results in a more gradual decline, indicating less sensitivity.
- The CER is further influenced by the time ratio (θ_i) and cost ratio (ϕ_i). The time ratio (θ_i) is the ratio of the average time per iteration in the aircraft to the average time per iteration in the simulator. A higher θ_i value indicates that the simulator is more time-efficient compared to the aircraft, leading to a higher CER and indicating better cost-effectiveness. The cost ratio (ϕ_i) is the ratio of the per-hour operating cost of the aircraft to the per-hour operating cost of the simulator. A higher ϕ_i value indicates that the simulator is more cost-efficient compared to the aircraft, also resulting in a higher CER.
- The trade-off between cost savings and training effectiveness becomes apparent as the simulation ratio increases. Decision-makers can use this visual representation to identify the optimal simulation ratio that balances cost savings and training effectiveness based on their specific requirements and constraints.

By incorporating the proficiency factor into the TER and CER formulas and providing a visual representation of its impact, we can better account for the potential effects of increased simulation on pilot proficiency. This enhancement allows decision-makers to make informed choices when determining the optimal mix of live and simulated flight hours in aviator training programs.

Introducing a Multi-Stage TER/CER (T/C) Model

Building upon the concept of the proficiency factor (α), we can further enhance the TER and CER formulas by developing a multi-stage model that accounts for the varying impact of simulation at different stages of a pilot's career. This approach acknowledges that the effectiveness of simulation may differ depending on the training phase, such as initial training, advanced training, or ongoing proficiency maintenance.

To develop a multi-stage T/C model, we introduce a new notation, β, which represents the stage factor. The stage factor is a numerical value that adjusts the proficiency factor based on the specific training stage. The value of β can be determined through empirical data analysis or expert input, reflecting the relative importance and effectiveness of simulation at each stage. The multi-stage TER formula can be expressed as:

$$\mathrm{TER}_{\alpha_\beta} = \alpha_\beta \left(\frac{Y_0 - Y_x}{X_i}\right) \tag{6}$$

where $TER_{\alpha\beta}$ is the stage-adjusted, proficiency-adjusted TER and α_{β} is the stage-specific proficiency factor. The stage-specific proficiency factor (α_{β}), used in Equation 6, is calculated by multiplying the proficiency factor (α) by the stage factor (β). This allows for a more nuanced adjustment of the TER based on both the simulation ratio and the training stage.

Similarly, the multi-stage CER formula can be expressed as:

$$\mathrm{CER}_{\alpha\beta} = \varphi_i \theta_i TER_{\propto\beta} \tag{7}$$

where $CER_{\alpha\beta}$ is the stage-adjusted, proficiency-adjusted CER and $TER_{\alpha\beta}$ is the stage-adjusted, proficiency-adjusted TER.

By incorporating the stage factor (β) into the TER and CER formulas, we can develop a multi-stage model that accounts for the varying impact of simulation across different training stages. This approach allows for a more comprehensive cost-benefit analysis that considers the specific requirements and effectiveness of simulation at each stage of a pilot's career.

To illustrate the multi-stage T/C model, let's consider an example with three training stages: initial training ($\beta_1 = 1.2$), advanced training ($\beta_2 = 1.0$), and ongoing proficiency maintenance ($\beta_3 = 0.8$). These β values suggest that simulation is most effective during initial training, equally effective during advanced training, and slightly less effective during ongoing proficiency maintenance.

Using these stage factors, we can calculate the stage-specific proficiency factors (α_β) and apply them to the TER and CER formulas for each training stage. This results in a more tailored cost-benefit analysis that accounts for the unique characteristics and requirements of each stage.

By developing a multi-stage TER/CER model, we can provide decision-makers with a more comprehensive and nuanced approach to evaluating the cost-effectiveness of simulation-based training across a pilot's entire career. This model enables the optimization of simulation resources and the development of stage-specific training strategies that maximize the benefits of simulation while minimizing costs.

Future Enhancements and Alternative Approaches

While the proposed enhancements to the TER and CER formulas, including the proficiency factor and the multi-stage model, provide a more comprehensive and nuanced approach to evaluating the cost-effectiveness of simulation-based training, there are other potential enhancements that can be explored in future research.

One area for further improvement is the expansion of cost factors considered in the CER calculation. In addition to the hourly operating costs of the aircraft and simulator, future analyses may incorporate elements such as instructor costs, maintenance costs beyond the hourly figures, and infrastructure costs associated with both live and simulated training. This would provide a more holistic view of the total costs involved in each training approach.

Another potential enhancement is the introduction of a readiness factor that directly ties the TER to specific readiness metrics or standards. By aligning the cost-benefit analysis with the operational objectives of the training program, decision-makers can ensure that the training approach not only optimizes costs but also effectively prepares pilots for real-world missions.

Overall, these alternative approaches emphasize the importance of a blended training strategy that incorporates a mix of live, virtual, and constructive simulations. Additive models such as the FAPV (Familiarize, Acquire Skill, Practice Skill, Validate Skill) model can be used to determine the optimal mix of training methods for each task, considering multiple factors such as student loads, instructor availability, and training device reliability (Morelle, 2016) (Frank & Helms II, 2000).

DATA COLLECTION AND ANALYSIS STRATEGY

To maximize the effectiveness of simulation-based training, organizations must implement a robust data collection and analysis strategy. This approach involves capturing comprehensive performance metrics from training devices across both institutional settings and deployed operational units. By leveraging advanced database management systems and integrating data from both simulated and live training, organizations can gain valuable insights to drive continuous improvement and ensure the optimal use of simulation resources.

Key data fields for collection may include task performance metrics, iteration counts, time to task completion, operating costs, maintenance costs, pilot performance indicators, incident reports, and training throughput. By leveraging a variety of data collection methods, such as automated logging systems, instructor observations, pilot surveys, and maintenance records, organizations can obtain a comprehensive and cross-validated dataset.

Establishing relevant metrics and key performance indicators (KPIs) is crucial for gauging the effectiveness and efficiency of simulation training. KPIs should be identified and tracked to assess the impact of simulation training on pilot performance, readiness, safety, and training throughput. These may include the Transfer Effectiveness Ratio (TER), Cost Effectiveness Ratio (CER), simulation training cost savings, pilot proficiency improvement, time to proficiency, safety incident reduction, training throughput increase, and return on investment for each simulation device.

Advanced database management systems play a vital role in handling large volumes of simulation data, ensuring accurate and conflict-free data handling, especially for parallel simulations. These systems should support data sharing between scenarios and devices, maintain compatibility across versions, and accommodate multiple data files and formats for detailed, varied training scenarios.

Integrating artificial intelligence (AI) and machine learning (ML) technologies with database management systems can provide valuable insights into training effectiveness (Mangaroska & Giannakos). AI-powered data analytics can identify patterns and optimize training scenarios, while machine learning algorithms can personalize learning paths, identify knowledge gaps, and provide targeted feedback to pilots.

Ensuring interoperability is essential, involving standardizing data formats and protocols, integrating data from different sources, and maintaining system flexibility for updates and changes. Real-time data exchange capabilities and effective data management strategies are also crucial.

Moreover, the adoption of flexible database solutions like NoSQL databases and hybrid approaches combining SQL and NoSQL servers can help organizations rapidly adapt to changing requirements, focusing on scalability and speed. By aligning simulated training data streams with live training data, organizations can achieve a closed-loop assessment of training impacts, enabling a holistic evaluation of how simulation-based training translates into real-world performance. This data-driven approach informs continuous improvements and optimizations, ensuring that simulation training remains effective and aligned with organizational goals.

Implementing a comprehensive data collection and analysis strategy requires addressing potential challenges such as ensuring data interoperability across multiple systems and establishing robust evaluation methodologies. However, the benefits of data-driven insights into training effectiveness and the ability to make informed adjustments based on empirical evidence make this a worthwhile endeavor for any organization committed to maximizing the value of their simulation-based training programs. This approach not only supports current training effectiveness but also provides a foundation for iterative enhancements based on real-world performance data, ensuring continuous improvement and alignment with evolving training needs.

ADDITIONAL CONSIDERATIONS

Fidelity and Experience Levels

The relationship between simulation fidelity and pilot experience levels is complex, with varying research outcomes. Some studies suggest that novice pilots may benefit more from lower fidelity simulations that focus on distinct skill sets, providing a manageable learning environment. Conversely, experienced pilots appear to derive more advantage from high-fidelity simulations that closely mirror real-world scenarios, allowing them to hone advanced skills and decision-making strategies.

However, the fidelity benefits might be task dependent. For example, emergency flight exercises may necessitate high-fidelity simulations for both novice and experienced pilots, as these scenarios demand precise visual scanning behaviors stress (Diaz-Piedra, et al., 2019). Ultimately, the choice of simulation fidelity should be informed by specific training objectives, mission complexity, and individual learning profiles. Empirical research metrics, such as performance, cognitive load, learning and retention, transfer of training, and eye-tracking data, can provide valuable insights when combined with standards and readiness training.

Mission Planning and Databases

Mission planning is a vital component of flight training simulations, demanding high levels of accuracy and real-time responsiveness. Incorporating high fidelity synthetic training environments that closely reflect real-world scenarios is essential for bridging gaps and enabling comprehensive mission rehearsal. This involves defining, processing, managing, and supervising intricate missions that encompass various dynamic and uncertain environmental conditions, such as crewed-uncrewed teaming, fuel consumption, task durations, and more.

Effective mission planning requires the integration of high-fidelity synthetic training environments that closely reflect real-world scenarios. This involves defining, processing, managing, and supervising intricate missions that encompass various dynamic and uncertain environmental conditions, such as crewed-uncrewed teaming, fuel consumption, task durations, and more. Advanced database management systems specific to mission planning can support the creation and management of these complex scenarios, enabling comprehensive mission rehearsal and bridging the gap between simulation and real-world operations.

Incorporating machine learning algorithms can enable personalized, adaptive learning paths, identify knowledge gaps, suggest relevant modules, and provide real-time performance tracking and feedback (Mangaroska & Giannakos). This approach allows for tailored training programs that address individual needs and learning styles, ensuring a more targeted and effective learning experience.

Emerging Technologies

The study evaluated the potential of emerging immersive technologies like virtual reality (VR), augmented reality (AR), and mixed reality (MR) in meeting aviation training fidelity requirements. These technologies present exciting opportunities to enhance simulation fidelity, particularly in the realm of visual representation.

Virtual Reality (VR) offers a fully immersive, computer-generated environment that can accurately replicate the visual cues and spatial relationships encountered in real-world flight operations. By leveraging high-resolution displays and advanced graphics rendering, VR systems can provide highly realistic and detailed visual representations of aircraft cockpits, landscapes, and environmental conditions. VR is used for immersive training experiences, allowing pilots to practice using aircraft controls and simulating emergency situations in a safe, virtual environment.

Augmented Reality (AR) technology overlays computer-generated elements onto the real-world environment, creating a blended experience. In aviation training, AR can be used effectively for mission-oriented training, flight-deck training, and maintenance activities, especially when users must react to complex situations and communicate efficiently.

Mixed Reality (MR) combines elements of both VR and AR, allowing for the seamless integration of virtual objects into the real-world environment. In aviation training, MR could enable trainees to interact with virtual representations of aircraft systems or components while still maintaining awareness of their physical surroundings.

While these immersive technologies offer exciting possibilities for enhancing visual fidelity and creating realistic training experiences, their implementation also presents challenges. Issues related to hardware compatibility, software integration, and cybersecurity must be carefully addressed to ensure the reliability and safety of these systems in mission-critical training environments.

Open, cross-platform standards, such as OpenXR, can significantly benefit the integration of virtual and augmented reality technologies into flight training simulations (The Khronos Group, n.d.). These standards reduce development time and costs by providing a common set of APIs for creating applications that run across a wide range of devices (Hongxiang, Lijun, & Kai, 2023). This approach promotes innovation, cost-effectiveness, and interoperability, enabling the development of a larger ecosystem of training applications that can be easily deployed and maintained across different platforms.

Embedded training is another promising area highlighted in the study. By integrating software-based tutors directly into the aircraft, it becomes possible to transform the platform into a versatile training tool that can be used in various settings, including hangars and ground-based environments (Hongxiang, Lijun, & Kai, 2023). However, the implementation of embedded training systems raises concerns related to the use of training threats on armed helicopters, potential cybersecurity risks, increased power consumption, and overheating (Hongxiang, Lijun, & Kai, 2023). These challenges must be carefully addressed to ensure the safe and effective deployment of embedded training solutions.

Deployed Mode Requirements

The study identified a notable gap in the current training systems: the absence of established requirements for deployable modes in simulation devices. Deploying simulation capabilities in operational environments can reduce the time and resources required for live training exercises, thereby increasing overall training throughput. Additionally, deployed modes can support non-combat-related training in environments where conventional training resources may be limited.

However, the demand for deployed simulation modes may vary based on operational contexts, particularly in high-intensity conflicts where training time is severely constrained. Addressing this gap by developing robust requirements and guidelines for deployed simulation modes represents an opportunity to enhance the adaptability and effectiveness of aviation training across a wide range of scenarios.

Accreditation Standards

Maintaining and updating pilot accreditation standards in the face of rapidly evolving simulation technologies presents several challenges. The study highlights key strategies for addressing these challenges and ensuring that accreditation standards keep pace with advancements in virtual reality (VR), augmented reality (AR), and mixed reality (MR) technologies (FasterCapital, 2024), (Dobrozorova, 2024), (Vardomatski, 2023).

One critical aspect is the continuous review and updating of standards to incorporate the latest technological developments. This requires establishing a framework for regularly assessing and adapting accreditation criteria to align with emerging capabilities and best practices in the field (FasterCapital, 2024). Collaboration with technology developers is essential to ensure that training programs remain compatible with cutting-edge technologies (FasterCapital, 2024).

Implementing adaptive regulations is another key strategy for keeping accreditation standards agile and responsive to technological changes. This entails creating flexible guidelines that can be easily modified as new technologies and methodologies emerge, allowing for a more dynamic and adaptable accreditation process (Dobrozorova, 2024). Furthermore, addressing regulatory and safety considerations associated with the use of VR, AR, and MR in training is crucial (Vardomatski, 2023).

By proactively addressing these challenges and implementing effective strategies, military aviation can ensure that pilot accreditation standards remain relevant, rigorous, and aligned with the latest advances in simulation technology.

CONCLUSION

This research challenges long-standing assumptions about the necessity of high-fidelity, full-motion simulators in aviation training, offering a more nuanced perspective on the relationship between simulation fidelity and training effectiveness. The findings from existing studies, highlighted in our analysis, suggest that seat-based motion cueing may provide training outcomes comparable to those of more expensive full-motion simulators for many tasks. This insight indicates significant potential for cost savings without compromising training quality, particularly in contexts where scalable solutions are necessary.

Our analysis, leveraging the enhanced Transfer Effectiveness Ratio (TER) and Cost Effectiveness Ratio (CER) models, underscores that the learning effects associated with high-fidelity simulators may not always justify their higher costs. For many training tasks, lower-fidelity solutions might offer a cost-effective alternative that maintains the essential elements of training transfer. This insight supports a strategic shift in military procurement, advocating for investment in targeted, adaptable simulation technologies that optimize resources and enhance training effectiveness across diverse operational scenarios.

The proposed framework for independently evaluating visual and motion fidelity enables a more precise tailoring of simulation capabilities to the specific needs of each training phase. This ensures that pilots receive the most relevant and effective training at each stage of their development, optimizing resource allocation while enhancing the adaptability and efficiency of training programs.

Additionally, addressing the lack of deployed mode requirements and implementing a robust data collection and analysis strategy, as discussed in our study, further enhances the flexibility and effectiveness of aviation training programs. Aligning procurement and training strategies with these findings will allow the military to provide advanced, efficient, and effective training to its pilots, even within resource constraints.

In conclusion, this research provides a roadmap for a more efficient, targeted, and cost-effective approach to simulation-based aviation training. By embracing these findings and adapting procurement and training strategies accordingly, the military can position itself at the forefront of simulation-based aviation training, ensuring that its pilots are prepared to meet the challenges of modern operations with the most relevant and impactful training available.

ACKNOWLEDGEMENTS

We thank the U.S. Army Program Executive Office – Aviation for their support and collaboration in this study. Their insights and guidance were invaluable in shaping the research and ensuring its relevance to the aviation community.

REFERENCES

Callendar, M. N. (2008). Transfer and Cost Effectiveness as Guides to Simulator/Flight Training Device Use. *The Collegiate Aviation Review International, 26*(1).

Diaz-Piedra, C., Rieiro, H., Cherino, A., Fuentes, L. J., Catena, A., & Di Stasi, L. L. (2019). The effects of flight complexity on gaze entropy: An experimental study with fighter pilots. *Applied Ergonomics, 77*, 92-99.

Dobrozorova, T. (2024, April 7). *Why VR is Essential for the Flight Industry in 2024*. Retrieved May 25, 2024, from HitBerry Games: Available: https://www.hitberrygames.com/post/vr-flight-training-why-vr-is-essential-for-the-flight-industry-in-2024

FasterCapital. (2024, April 2). *Aviation Training Integration: Breaking Barriers: Integrating Virtual Reality into Pilot Training Programs.* Retrieved from https://fastercapital.com/content/Aviation-Training-Integration--Breaking-Barriers--Integrating-Virtual-Reality-into-Pilot-Training-Programs.html

Federal Aviaition Administration. (2023). *Air Carrier Training Aviation Rulemaking Committee Recommendation 23-1: Simulation Training Devices Suitable for Spacial Disorientation Training.* Flight Standards Service.

Frank, G. A., & Helms II, R. F. (2000). Determining the Right Mix of Live, Virtual, and Constructive Training. *Proceedings of the 21st Interservice/Industry Training Systems and Education Conference.*

Hongxiang, Z., Lijun, Y., & Kai, D. (2023). Design and Implementation of Airborne Embedded Training System. *IEEE International Conference of Image Processing and COmputer Applications (ICIPCA)*, (pp. 1139-1143).

Mangaroska, K., & Giannakos, M. (n.d.). Learning Analytics for Learning Design: A Systematic Literature Review of Analytics-Driven Design to Enhance Learning. *IEEE Transations on Learning Technologies, 12*(4).

McCauley, M. E. (2006). *Do Army helicopter training simulators need motion bases? (ARI Technical Report 1176).* Arlington, VA: U.S. Army Research Institute for the Behavioral and Social Sciences.

Morelle, D. (2016). Live Versus Virtual: Cost Benefit Analysis for Applying Simulation Towards Army Aviation Flight Minumums. *Electronic Theses and Dissertations, 5328*. Retrieved from https://stars.library.ucf.edu/etd/5328

Myers, P. L., Starr, A. W., & Mullins, K. (2018). Fight Simulator Fidelity, Training Transfer, and the Role of Instructors in Optimizing Learning. *International Journal of Aviation, Aeronautics, and Aerospace, 5*(1).

Sparko, A. L., & Bürki-Cohen, J. (2010). *Transfer of Training from A Full-Flight Simulator vs a High Level Flight Training Device with a Dynamic Seat.* John A. Volpe National Transportation Systems Center, Department of Transportation, Federal Aviation Administration.

Stanney, K., Hughes, C., Fidopiastis, C., & Jasper, A. (2021). Augmented Reality in Tactical Combat Casualty Care: Physiological Ramications . *Interservice/Industry Training, Simulation, and Education Conference (I/ITSEC).* Orlando.

Stewart, J. E., Johnson, D. M., & Howse, W. R. (2008). *Fidelity Requirements for Army Aviation Training Devices: Issues and Answers.* Arlington, VA: U.S. Army Research Institute for the Behavioral and Social Sciences.

The Khronos Group. (n.d.). *OpenXR Overview*. Retrieved May 9, 2024, from The Khronos Group: https://www.khronos.org

Vardomatski, S. (2023, February 24). *VR for Flight Training Benefits and Challenges*. Retrieved May 25, 2024, from Forbes: https://www.forbes.com/sites/forbestechcouncil/2023/02/24/vr-for-flight-training-benefits-and-challenges/

Woody, C., Goldie, C., O'Brien, K., Aura, C., Case, J., & Delgado-Howard, C. (2020). *Aviation Training Next: Is VR Effect in Initial Rotary Wing Training?* Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory.