B-52 Pilots in Focus: Human Factors in Virtual Reality Research

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ABSTRACT

Virtual Reality (VR) is emerging as a valuable training tool to reduce the resources required for training in many flight tasks. This novel research focuses on pilots learning how to successfully perform in-air refueling tasks with the help of VR. To train Airmen effectively and efficiently in this advanced training environment, human factors tools were integrated with learning theory research to develop recommendations. Utilizing the Applied Cognitive Task Analysis (ACTA) methodology, researchers mapped the process of successfully completing the in-air refueling task. With eye-tracking technology embedded in the virtual reality headset, this effort focused on identifying training inefficiencies by monitoring and tracking ocular activity during in-air refueling. Using both visual graphics and statistical comparison, five areas of interest were identified for each pilot's VR attempt. Instructors' data served as a baseline comparison to the students' data. This process allowed researchers to observe where the B-52 pilots are looking relative to where they should be looking based on the results of the ACTA, during the in-air refueling task. In addition to analyzing pilot performance in VR, structured training model recommendations were identified. Based on the foundation of the SEEV (Salience, Expectancy, Effort, Value) model, the Four Component Instructional Design (4C/ID) Model was ultimately integrated to create a proposed learning framework, fusing the traditional learning process with the use of virtual reality as a supplemental training tool. Targeted learning objectives in a multi-scaffolding transfer of training approach were developed with an emphasis on human factors supported improvements to the interface in the VR simulation. Recommendations included modifying the VR simulation, integrating the part-task process, and increasing instructor training. Incorporating virtual reality as a training tool, with a structured learning approach and ease of information, has the potential to supplement and improve training efficiencies for specific in-air tasks.

ABOUT THE AUTHORS

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INTRODUCTION

Training processes for pilot critical mission tasks, such as air-refueling can be enhanced using advanced cognitive and physiological technologies. The U.S. Defense Forces have incorporated advanced training technologies at all levels of tasks and in all types of environments, though often without a training methodology to support the instructors tasked with integrating them. This has resulted in high-tech training equipment being implemented with a conventional training model and syllabi that doesn't blend easily. After looking at the U.S. Air Force's implementation of virtual reality training tools designed specifically for critical mission tasks, such as air-refueling, the need for a better training model is evident.

As technology has adapted first to non-motion base simulators, then motion, and later to virtual and augmented reality simulation, training protocols have adapted at each level. The defense aviation industry continues to embrace the technological advancement that Virtual Reality (VR) simulation provides. The Air Force began testing the benefits of incorporating more VR training programs with its Pilot Training Next (PTN) VR training program to speed up pilot training and make it more cost-effective (Naval Air Warfare Center Training Systems Division, 2019. By leveraging integrated eye-tracking technology within immersive flight simulation environments, we concentrated on the following objectives:

- Identify training inefficiencies in in-air refueling training using Applied Cognitive Task Analysis (ACTA) methodology and eye tracking technology.
- Define potential improvements to maximize the desired outcome of available advanced learning tools.

The use of eye tracking technology to enhance training programs is a methodology that is gaining more traction as research advances. This technology allows researchers to observe a pilot's areas of focus in granular detail, which in turn can communicate a good deal about the pilot's stress levels, thought processes, and even confidence. This research investigates a highly cognitive and visually demanding operator task: air refueling. Ultimately answering the question: are instructors and trainees using the visual cues and references adequately/correctly while completing the air refueling task?

Our research determined that the training methodology would be more consistent and effective if a learning model was incorporated into the design of the program. As there are limited models that are designed and/or tested in a virtual reality training environment, we found support for the development of an integrated model.

BACKGROUND

VR Learning Environments

Many researchers are now exploring the psychology of VR as a learning and training tool across various industries. Van Weelden's recent research examined VR specifically for aviation training (Van Weelden et al., 2021). Positive impacts on pilot cognition are evident as the understanding of both psychological and technological improvements advances (Budgeon et al., 2022). The defense aviation industry is embracing the advancements VR simulation provides, with the U.S. Military budgeting an estimated $14 billion for virtual training programs (Garcia & Winer, 2022). With the implementation of Pilot Training Next (PTN), now known as Pilot Training Transformation (PTT), the Air Force is testing the benefits of incorporating more VR training programs to expedite pilot training and improve cost-effectiveness (Hawkins, 2019). PTN focuses on understanding the learning process of Airmen and "prototyping training environments" using different technologies to accelerate the pilots' learning process (Hawkins, 2019). The ability to manipulate the training environment to any scenario in a controlled setting is a clear advantage of incorporating VR in defense training (Garcia & Winer, 2022). Van Weelden (2021) also references the benefits of safe and controlled environments resulting from VR training.

The use of VR as a training tool extends beyond the Air Force, having been implemented in each branch of the military. The Navy has also utilized VR for training its naval aviators. Four different training squadrons are adapting to a syllabus that incorporates immersive training technology, with the first class completed in February 2022 (Chapman, 2023). This program, introduced through the Naval Aviation Training Next (NATN) initiative, aims to prepare pilots better for cognitive adaptation (Blow, 2023). The Navy's focus on this technology mirrors that of the Air Force: to produce pilots with more experience and competency in less time.

Eye Tracking in Learning Environments

The human eye is a powerful tool. With the development of eye-tracking technology, science has created a window into the human brain. Vision accounts for 70% of the body's sensory receptors and can even influence other senses into forming positive or negative thoughts based on visual appearance (Watts, 2017). Eye-tracking involves the observation or monitoring of eye movements and fixations using an invisible near-infrared light and high-definition cameras to project light onto the eye and record the direction it's reflected off the cornea (Tobiipro, 2022). Once the human eye identifies something of interest, our eyes examine the item or feature, causing the pupil to contract or dilate depending on the triggered emotion (Watts, 2017). This is known as a fixation. The movement to the points of vision, known as a saccade, is equally valuable to researchers. Fixations and saccades can provide extensive information about the cognitive processes of the subject. The development and enhancement of eye-tracking technology allow researchers to observe human reactions and behaviors beyond what the naked eye can see, creating a new avenue to determine how subjects process situations and mentally plan actions.

Eye-tracking glasses are designed to record a person's gaze activity in real time across a wide range of applications and scenarios (Skvarekova & Skultety, 2019). Eye-tracking devices and technology can test and track human subjects in various applications, not just aviation. For example, research published in 2022 examined predicting drivers' intentions to change lanes using eye-tracking technology (Pan et al., 2022). While the results suggested the device was useful for prediction, challenges remain in determining the optimal time window for feature extraction (Pan et al., 2022).

Eye-tracking technology has also been proven to identify more experienced or learned professionals. In various industries, studies have shown similar assessments. For instance, Comu et al. (2021) evaluates three groups of construction workers at different skill levels at a construction site using eye-tracking glasses. The research indicated that different backgrounds or groups played a crucial role in adaptation and concentration levels (Comu et al., 2021). Similarly, in aviation, Skvarekova & Skultety (2019) found that inexperienced pilots managed between 100 and 120 saccades per minute, while experienced pilots could exceed this number by up to 40%.

METHODS

A combination of data collection methods was used for the evaluation and development of findings and recommendations (see Figure 1).

Instructional Video/Interviews

The Applied Cognitive Task Analysis (ACTA) method (Militello et al., 1997) was used to gather detailed information on the cognitive processes of air refueling experts. The ACTA method comprises four main steps: Task Diagram, Knowledge Audit, Simulation Interview, and Cognitive Demands Table. This set of interviews, diagrams, and tables identifies skills and cognitive resources needed to adequately perform a task and assists in communication between the researcher/practitioner and Subject Matter Experts (SMEs). The cognitive demands table identified the specific activities of the task performance as well as the visual areas on which to focus, also referred to as areas of interest (AOI), in the eye tracking and statistical analysis.

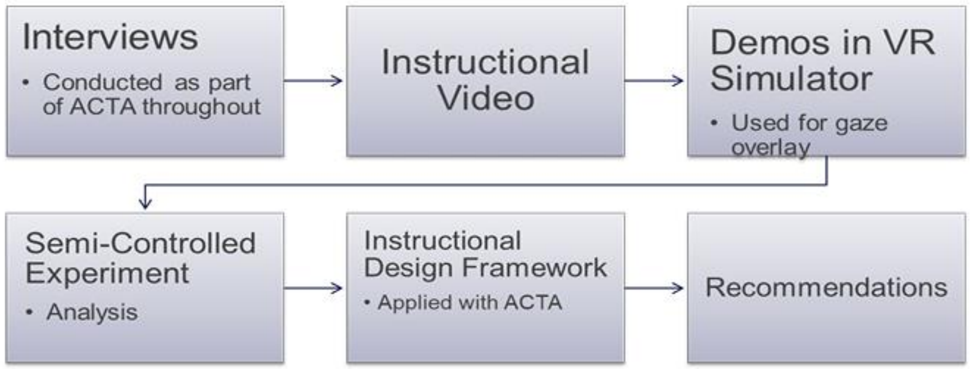

Figure 1. Data Collection Flowchart

Four experts (pilot instructors) provided input for the ACTA. The following sections describe each of the steps in completing the analysis.

The simple task diagram (see Figure 2) is designed to provide a broad overview of the key parts of the task and aid in identifying difficult cognitive elements. From our initial discussions with the SMEs, these are the broad task steps identified in the task diagram.

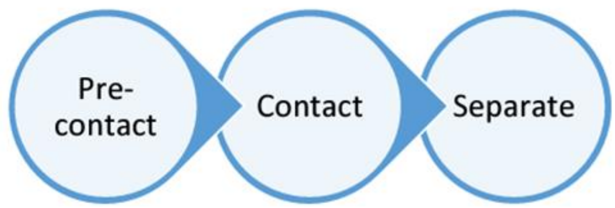

Figure 2. Simple Task Diagram

We began with an unclassified instructional video used for in-air refueling training. This video provided an inside look, from the B-52 pilots' perspective, at the task and vantage point before and during the task. This, roughly sixteen-minute video shows the visual references that are used to successfully complete this task as well as movement limits.

A series of interviews were conducted with subject matter experts to capture further details not covered in the instructional video. These included simulation interviews using the VR system. There were two different VR simulator set-ups that we observed; one using a Varjo XR-3 headset and the other using a Vive headset. We recorded the run with a cell phone recording the screen with the gaze points showing, manually going back to watch the gaze dot to follow the areas of interest that the pilot focused on.

We were able to take the instructional video and overlay the gaze from the recordings from observing the student trainee and the instructor in the simulator. The following figures show a sequence of scenes with the visual references marked at each stage of the refueling process in an attempt to map eye-tracking recording.

Figure 3. Precontact - Left Seat Reference Points

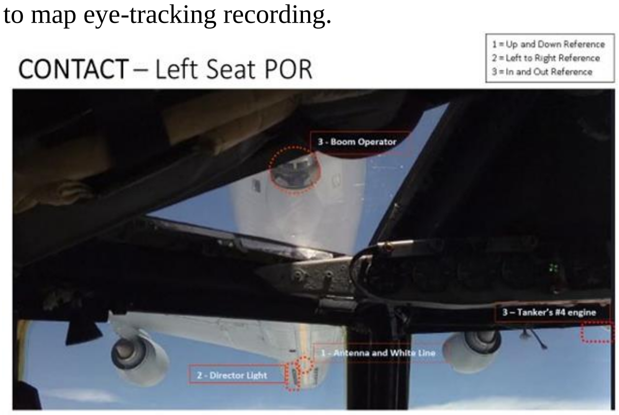

Figure 4. Contact - Left Seat Reference Points

Cognitive Demands

The Cognitive Demands Table (see Table 1) pulls together all the components of the ACTA to create a diagram that easily conveys to decision-makers a summary of the most cognitively demanding aspects of the task. Each identified difficult cognitive element is defined, along with a short description of why it is difficult, the errors most commonly associated with that element, and the cues and strategies used by the expert to make the task more manageable. This information was then used to assist in making the training recommendations presented. The output from the cognitive task analysis was critical to combine with information gleaned from the demonstrations in the simulators and the data analyzed from the semi-controlled experimental runs.

The ACTA informed us that B-52 pilots that successfully conduct in-air refueling, experience five different cognitively demanding components pertaining to; 1) distractions, 2) environmental layout, 3) duration of task, 4) physical strain, and 5) situational awareness. These five components are identified and defined more specifically within Table 1. For each difficult task, we were able to identify cues and strategies that ultimately help lead to success. That then informed our team what were the most important components to observe while dissecting the eye tracking data from the VR simulation.

Table 1. Cognitive Demands Table for In-Air Refueling

B-52 Pilot In-Air Refueling - Cognitive Demands Table			
Difficult Cognitive Element	**Why Difficult?**	**Common Errors**	**Cues and Strategies Used**
Getting distracted by the boom's proximity	The pilot's focus should be on the 3D visual reference points, however, the boom's proximity to the window of the cockpit comes unnervingly close. For the novice can become distracting and cause mental distraction	Losing focus of the 3D visual reference points	Maintain visuals of 3D reference points
Mirrored cockpit controls	The gauges/controls in the B52 are mirrored from pilot to copilot which is a departure from any other aircraft in the U.S. Air Force fleet.	Forgetting the placement of gauges/controls in B52	Awareness and memory
Length of time for refueling	The B52 can take up to 18 minutes to refuel. Maintaining a stable contact position while the boom is engaged is both physically and mentally challenging for a pilot.	Not self-monitoring physical/mental status	Personal awareness (self-monitoring) of cognitive load, disengage the boom physical/mental focus lags
Maintain steadiness of aged and cumbersome aircraft	The B52 could be labeled an antique aircraft in terms of technology, size, shape, and aerodynamics. As a result of a combination of these factors, the aircraft tends to 'walk and waddle' during flight. The aircraft's size also results in a delayed reaction to the pilot(s) commands.	Overcorrecting movements when the aircraft is simply slower to respond to the original desired in air placement	Maintain 3D visual references
Maintaining Situational Awareness	Continuous monitoring is required, very few outside references and many cues are difficult to see (not salient)	Experiencing tunnel vision, missing a cue due to unreliability or difficulty distinguishing it.	Keep gaze moving to monitor all relationships between cues

Pilot Data from Semi-Controlled Experiment

The compilation of the details gleaned through the ACTA process provided direction on the type of data that should be captured from human operators to answer the following research questions: 1) are the pilots, both trainees and instructors, in fact using the cognitive strategies and visual cues they are trained to use, 2) having identified the areas of interest, how long does it take the pilot to fixate on each of the areas of interest, and 3) is there a difference in the pilot's visual behavior during contact and disconnect with the boom?

To answer these questions we conducted a semi-controlled experiment working with the B-52 Formal Training Unit (FTU) in the 11th Bomb Squadron at Barksdale Air Force Base. Twelve VR-simulated flight runs were captured in total. Unfortunately, two of the files were corrupted, resulting in ten flight runs to use in analysis; five students and five instructors. Each run was to have a minimum of two 'connects' with the boom and to be at least ten minutes in length. This request was met by each subject with more than two connects for all pilots, and an average flight length of 18 minutes, 46 seconds. Data was captured using Varjo Base with eye tracking collection turned on.

Once the flight runs with eye tracking and gaze data were captured we were able to set up our analysis and statistical measures. We designated areas of interest (AOI) based on the information collected from the ACTA, which helped in identifying the visual reference points most needed to successfully accomplish the in-air refueling task. Five areas were created as the focus of our initial analysis as shown in Figure 5: antenna and while line, boom operator, engine #2, engine #3, and the control panel. While the stinger light was a visual reference identified throughout the ACTA, the visuals of pre-contact to contact the VR simulation did not provide a usable reference.

The recordings of two SME demo flight runs in the VR simulator were captured and used to test our semi-controlled experiment. We manually observed and marked the time stamp made of each of the eye movements throughout both of these demo runs. This manual dive into the SME's actions helped us also to verify what we had gleaned through the ACTA insights. There were no additional focus areas of interest, beyond the five established, that the pilots were observing for us to note specifically in this step. Just in this short run, we were able to observe an example of tunnel vision and lack of ocular movement that we will look into further as we analyze the gaze data from the semi-controlled experiment.

Transfer of Training Models

Wicken's SEEV (Salience, Expectancy, Effort, Value) model was looked to for the visual components of this training methodology (Wickens et al., 2003). There was still a gap, as the SEEV model emphasizes visual focus, our full objective needed to include accomplishing training transfer in a high-level, cognitively demanding task. For this, we found support for integrating van Merriënboer's Four Component Instructional Design (4C/ID) Model (Van Merriënboer, 2019) with the SEEV model. The 4C/ID model is made up of four components; with subcomponents to construct the complete model. The four key components are as follows; 1) design the learning tasks, 2) design the supportive information, 3) design procedure information, and 4) design part-task practice (Van Merriënboer, 2019). These integrated four parts would enhance the transfer of training. Specifically, the presentation and repetitive execution of a task, help the student create a knowledge base. Students then use this knowledge base to be able to pull information from memory to apply to new situations. By gradually increasing complexity and decreasing the support and guidance provided, this helps the student learn to coordinate different aspects of performance and combine acquired skills, knowledge, and attitudes. In addition, distinguishing between routine and non-routine aspects of the complex task helps the students perform the routine tasks faster, reducing cognitive load, allowing them to use cognitive resources for non-routine aspects.

RESULTS

Research Questions

I) Do pilots follow the prescribed cognitive strategies?

A comparative analysis between the instructors and students to look into the cognitive actions of the pilots was conducted utilizing iMotions software. For each pilot, we generated a heat map of their gaze during the entire flight. We used those individual gaze maps to generate aggregate heat maps of the instructors (see Figure 6) as well as the students (see Figure 7). The areas of interest (AOIs) are identified in Figure 5 using the colored areas in the image, correlated with the legend indicating the area and corresponding AOI.

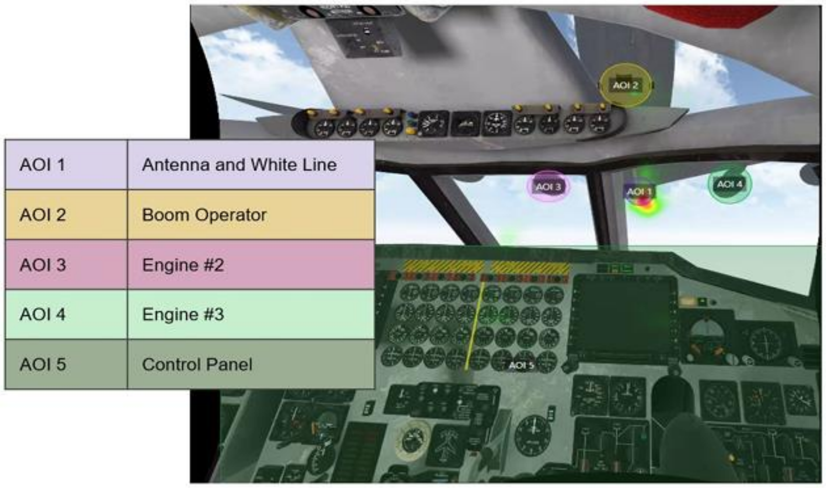

Figure 5. Areas of Interest (AOIs)

The images show a clear visual distinction from where the instructor pilot's focal emphasis is throughout the flight versus that of the students. The heat map is arguably one of the best indications, in the imagery collected, as it shows the highest area of focal concentration as the color progresses from green to red, red being the most concentrated. In Figure 7 we observe that the student pilots appear to visually take in more of the reference points as compared to the instructor eye movement in Figure 6. The instructors' gaze is hyper-focused on the antenna/white line area of the screen while we can see the students' focus is more spread out.

Figure 6. Aggregate Heat Map of Instructors

Figure 7. Aggregate Heat Map of Students

II) **How long does it take for the pilot to fixate on each of the defined AOIs?**

After this initial analysis observing the emphasis that the pilots put on the different AOIs, we wanted to look deeper and determine when the pilot's attention was first going to the AOI. To answer this we looked at the 'time to first fixation' (see Table 2). The time to first fixation is measured in terms of seconds. Immediate distinctions include the first fixation of the aggregate of each pilot group are not the same. The instructors looked at the antenna and white line one second into the flight, while it took the students roughly twenty seconds to look at the same AOI. Of further interest, the students first looked at the boom operator, contrasting the first fixation for the instructors. It is also worth noting how long it was before the instructor observed engine #3, roughly six minutes. These data points can be used to inform where the pilots are focusing, and when. This also allows us to see what level of import the pilots of different experience levels attribute to the AOIs.

Table 2. Time to First Fixation (TTFF) in seconds

AOI	Instructor	Student	Difference
Antenna/ White Line	1.04	20.7	-19.66
Boom Operator	21.2	13.2	8
Engine #2	65.7	58.8	6.9
Engine #3	367.9	84	283.9
Control Panel	262	306.9	-44.9

III) **Is there a difference in gaze behavior during contact and disconnect?**

After observing overall visual behavior, we took a closer look at what is happening prior to, and during the time they are connecting with the boom, since the end goal of the task is to be able to connect with the boom and transfer fuel. Flight runs were manually observed and marked for 'connect through disconnect' blocks of time. This data was manually entered into the iMotions software. Following the time blocks being marked in the software, we then manually adjusted the AOIs to a granularity of every 50 milliseconds, which ensured the gaze data being captured was at the points we are interested in observing.

Table 3. Pilot's connection times

Pilot #	Participant Level	Total Connection Time
2	Instructor	11:09.0
3	Instructor	11:27.0
4	Instructor	01:22.3
10	Instructor	13:09.1
11	Instructor	05:31.1
5	Student	10:32.4
6	Student	03:36.0
7	Student	11:46.8
8	Student	00:56.7
9	Student	09:05.4

The instructors averaged 10:19 minutes of time connected with the boom, while the students averaged 7:11.5 minutes. Data for each pilot's connection times are shown in Table 3. We identified an outlier in our pool of instructor data with an unusually low time for connection. Due to this we omitted the pilot's time from this analysis. This analysis further informed that the antenna and white line was the most valued AOI by both instructors and students at connect and disconnect. As indicated in Table 4, the instructors' gaze was at the antenna and white line 79% of the time when connecting to the boom and 88% of the time when disconnecting from the boom. In contrast, the student's gaze was at the antenna and the white line 78% of the time when connecting to the boom and 82% of the time when disconnecting from the boom. It is also relevant to note the continued evidence that the students value the boom operator reference point more than the instructors do, based on the statistical gaze data.

Table 4. Pilots gaze at connect and disconnect from the boom

		Antenna & White Line	Boom Operator	Control Panel	Engines #2 and #3
Instructor	Connects	80%	16%	3%	1%
	Disconnects	92%	8%	0%	0%
Student	Connects	79%	21%	0%	0%
	Disconnects	83%	15%	0%	2%

DISCUSSION AND RECOMMENDATIONS

Using the knowledge gained from the ACTA, and data collected supporting the visual cues and analyzed from the semi-controlled experiment, we were able to identify cognitive challenges experienced by the pilots and, from these, determine associated training needs (see Table 5). The recommendations address the training process itself, and several are straightforward, low-cost, and relatively easy to implement. By implementing the recommendations the process would be streamlined, making the training more efficient from the instructors' perspective and consistent for pilots. We concluded our recommendations with a proposed adaptive learning framework with elements that have been proven to aid in the transfer of training.

Table 5. Summary of challenges and training needs identified

ACTA: Difficult Cognitive Elements	Challenge	Training Need
Getting distracted by the boom's proximity	Maintaining focus on visual reference points	Train sequence of monitoring visual references, understanding visual illusions, Overcoming tunnel vision
Mirrored cockpit controls	Control placement confusion	Train in both left and right seat
Length of time for refueling	Physical/mental challenge over the duration of refueling	Incorporate physical aspects, if possible, lengthy training sessions, proper positioning, and movement
Maintain steadiness of aged and cumbersome aircraft	Determine corrections and movement needed	Practice for instinctive response
Maintaining situational awareness	Periods of high cognitive demand	Vary starting points of training scenarios, error recovery training

Recommendations

The implementation of a strong learning model that bridges the gap between conventional training syllabi requirements and modern technology is critical to realizing the highest benefits of enhanced training technology (VanMerriënboer, 2019) . Based on our research, the 4C/ID model provides a valuable framework to build upon and integrate with other validated learning models that gear to the conventional training needs. To this point, the implementation of VR format into conventional learning environments, such as air refueling, has been largely by trial and error and with little cohesion throughout the program. With an increased focus now on effectively implementing this technology, the application of an instructional design framework will help achieve this goal (Van Weelden et al., 2021)).

Part-task practice breaks the task out into specific scenarios with different environmental conditions or other elements that may affect performance demands. Part-task practice helps to fully automate routine aspects, focusing on accuracy, then speed and then time-sharing of pilot's mental resources. One way to approach development of scenarios is to have the student "dropped in" space, where they have to gain situation awareness and connect. Part-task practice also aligns with scaffolding and can include a complexity progression through the training process.

Feedback is an important element identified as critical throughout the entire training process. The key is determining when and how the feedback is most beneficial (Wisniewski et al., 2020). By employing a scaffolding approach with guidance and support from the instructor decreasing across training sessions, more feedback should be provided to the student in early training sessions. Feedback can be provided immediately to the student through the instructor or potentially with pop-up windows (use this with scaffolding and complexity building as this can be distracting). Incorporating the annotation feature in the secondary screen provides the instructor with an easy option to provide durable feedback to the trainee.

Using gaze overlays as a form of feedback allows the students to critically compare their own mental models and cognitive strategies with those of the instructors. Eye-tracking can be a useful tool to do this overlay and to compare post-task or provide a real-time view for the instructor.

Lastly, ensuring that the instructor has a knowledge base of the similarities and differences in the VR simulator versus in the plane, and how one translates to the other will improve their ability to use the VR as an effective tool (Hubscher-Davidson & Borodo, 2012) . In addition, training the instructor on how to use and implement the scenarios in the VR simulator to support scaffolding will aid in training transfer. This not only increases the instructor's knowledge base, but also increases motivation to effectively use the system.

CONCLUSION

By incorporating strong human factors concepts into the VR simulation, students have an enhanced opportunity for training transfer. The visual components of the simulation can profoundly impact reaction time during tasks. To create the necessary sense of realism for cognitive training, the simulation must closely resemble the "in-the-jet" environment. This helps pilots learn what objects and cues to look for and where to find them once they transition into the actual jet. Any gaps or discrepancies between the simulated and real environments can cause mental delays as pilots sift through their memory. Ultimately, the purpose of the training model is to reduce the cognitive effort required from pilots when they perform tasks in the jet.

The implementation of virtual reality into the formal training program and syllabus has the potential to reduce the cost and time required to train pilots if done correctly (Gouedy, in preparation). The Government Accountability Office (2022) report estimates the cost to operate the B-52 to be approximately $88,000 per hour. Enhancing the current training process to meet proficient goals in less time and with fewer in-air practice equates to real-world cost impact to the command. The VR tool provides a novel approach to training for the Formal Training Unit (FTU) at Barksdale Air Force Base. The FTU currently does not have an applied method for training pilots in the air refueling task outside of the actual aircraft. The aircrew training devices currently lack components for sufficiently training air refueling on the ground. Additionally, these traditional training devices are much less accessible and, in most cases, require a higher cost to operate compared to the VR application. Therefore, implementing not just the VR tool, but also a structured approach to this task, is crucial for achieving measurable success. By incorporating the VR training tool with a well-designed learning model, pilots can learn the visual cues and environmental feel of in-air refueling in a low-stress, safe and easily accessible environment.

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