Time to Put Down the Sticks and Put on the Headset…

Training Fighter Aircrew in the 21st Century

By

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Biography

Major Benjamin Lee is assigned to the 334th Fighter Squadron, 4th Fighter Wing, Seymour Johnson AFB, NC. Maj Lee started his USAF career in the enlisted corps as an RC-135 Airborne Systems Engineer during which he earned his Bachelor of Science in Criminal Justice Administration from Bellevue University and was commissioned through the USAF's Officer Training School. He completed Joint Undergraduate Navigator Training at NAS Pensacola, Florida and went on to serve as an F-15E Instructor Weapons System Officer (WSO) at RAF Lakenheath, United Kingdom, Evaluator WSO/Operational Support Squadron Director of Staff at Mountain Home AFB, Formal Training Unit Evaluator WSO/Chief of Fighter Wing Advanced Programs at Seymour Johnson AFB, NC., and Deputy Strategy Plans Team Chief at the 613th Air Operations Center, Joint Base Pearl Harbor-Hickam, HI. Maj Lee has over 1200 hours in the F-15E Strike Eagle and has combat time in both OPERATION ODYSSEY DAWN and OPERATION ENDURING FREEDOM.

Abstract

Fighter aircrew training in the 21st Century still utilizes instructional methods developed in the early years of WWII aerial combat. Using low fidelity visual aids such as aircraft sticks, hand drawn 2D lines, and hand drawn pictures to instruct fighter aircrew may have proven effective for the last 70 years, but the ever-increasing cost of operating advanced fighters precludes aircrew from compensating for archaic instruction with experience gained through bulk of flight repetition. Resource constraints combined with constantly expanding mission complexity demands that the United States Air Force (USAF) must take a fresh look at ways to increase instructional efficiency in fighter aircrew training. Recent advancements in commercially available Virtual Reality (VR) technology presents a unique opportunity for the USAF to re-design its approach to basic fighter aircrew instruction. Increased instructional effectiveness through implementation of VR in fighter aircrew academic training, instructional briefing, and flight debrief, has the potential to significantly decrease the cost of basic aircrew training while also providing increased opportunities for training to the advanced mission sets required for combat against a peer adversary such as Russia or China.

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Introduction: The 21st Century Pilot Production Quagmire

"We are in a crisis…We're 1,500 pilots short, and if we don't find a way to turn this around, our ability to defend the nation is compromised"

- General David Goldfien, USAF Chief of Staff[1]

There are three major components to resolving the current aircrew shortage: Recruiting, Training, and Retaining. The USAF is developing major initiatives designed to increase fighter aircrew retention and redoubling its focus on recruiting more applicants in the United States Air Force Academy (USAFA), Reserve Officer Training Corps (ROTC), and Officer Training School (OTS). Unfortunately, commercial airlines are experiencing a similar pilot shortage, and are able to offer high pay, location stability, and short work weeks. This presents a very appealing alternative to the moderate pay, short duration assignments (2 ½ to 3 years), and high operations tempo with multiple deployments experienced by USAF pilots. This environment has resulted in an average deficit of 369 pilots per year over the last 5 years (see Table 1).[2] Even if the USAF was able to drastically increase retention, the USAF will need to find a way to fill the 1,500 pilot debt discussed by Gen Goldfien.

Fiscal Year	Pilot Production	Pilot Losses	Surplus/Deficit
2014	930	1735	-805
2015	780	1139	-359
2016	775	1029	-254
2017	851	1008	-157
2018	886	1156	-270

Table 1. FY14-FY18 Annual Pilot Production vs. Accession

Recovery from this aircrew debt requires an increase in pilot production that starts with recruitment. While recruitment for pilots has generally been a relatively easy proposition, recruitment campaigns in the last decade have focused on breaking the perception that all the USAF does is fly fighters, concentrating its efforts on recruitment of cyber warfare, space warfare, and unmanned aerial vehicles (UAVs). This has come at a cost to pilot recruitment, thus garnering a concerted re-focus on pilot recruitment in order to ensure the requisite pool of aircrew accessions.

The increase in pilot/weapons system officer (WSO) accessions has exposed the training pipeline as the most restrictive factor in the complex fighter pilot crisis equation. One of the USAF's Air Education and Training Command commissions is to develop and train fighter pilots and combat systems officers (CSO) with the basic skills to safely operate jet aircraft. This process is known as specialized undergraduate pilot/CSO training (SUPT/SUCT), and generally takes approximately one year to complete. After the completion of undergraduate training, pilots and CSOs receive an additional year of airframe specific operating and employment training before becoming combat mission ready (CMR). This two-year training pipeline to produce fighter pilots and WSOs presents an "absorption limitation" as the USAF must find a way to produce more pilots/WSOs than it loses on a consistent basis. [3]

Innovative programs such as Pilot Training Next (PTN) have the potential of cutting undergraduate training time down to six months, but airframe specific training is limited by instructor manning, aircraft availability, and financial constraints. Without innovative solutions to increase airframe specific training, the temptation will be to reduce the number of flights required in the initial qualification training (IQT) and mission qualification training (MQT) syllabi. Reduction in syllabus events would be a costly exchange of combat capability for increased production. Not only does this approach ultimately risk a decrease in the USAF's primary warfighting mission, but the mass production of minimally capable aircrew would likely be accompanied by safety concerns reminiscent of WWII pilot production.

The increased demand on the formal training unit (FTU) enterprise due to the aircrew manning crisis is further exacerbated by the increasing military capability of near-peer potential adversaries such as China and Russia. As identified in the 2018 National Security Strategy and National Defense Strategy, these countries have made significant advances in military technology over the last decade. This approach towards military parity places additional demands on the FTU, as USAF combat squadrons require incoming IQT aviators to have increasingly more complex skills. To achieve the basic level of tactical knowledge demanded by these advanced threats, the FTU F-15E syllabus should be expanded to include introduction to tactical problem sets such as defensive counter-air (DCA), operations against long-range air-to-air missile threats, and operations in an anti-access area denial (A2AD) environment. The addition of such training under the current training methods would increase the length of training by an estimated 1-2 weeks, resulting in a slight annual production decrease of F-15E pilots and WSOs.

This paper will argue that the introduction of Virtual Reality technology has the capability to dramatically increase the quality of fighter aircrew training in the formal training unit (FTU), ultimately making the FTU more efficient at producing more lethal pilots and WSOs in a resource constrained environment.

Current Flight Training Techniques

When instructing within visual range maneuvering, the USAF fighter community uses a mantra of "Cue, Action, Mechanics" to ensure students understand the appropriate scenarios in which they should execute a specific tactic/maneuver and how to physically fly the maneuver in the flight briefing before they step to fly the mission. This construct has proven effective in training fighter aircrew, and has been adopted as the industry standard for flight instruction methodology. When Major Kellen "Trump" Sick was the F-15E Basic Fighter Maneuvers

(BFM) phase manager at the USAF Weapons School, one of his primary goals was to instill in the Weapons School students that the purpose of an instructional BFM flight brief was to create a "high-fidelity chair fly" of the upcoming mission.[4] This involved combining verbal description with visual representation of aircraft position using miniature scaled aircraft models augmented by crude dry erase (or chalk) drawings of a first person perspective of what the student pilots should see airborne. An example of this would be the following narrative to describe when and how to execute a defensive break:

> "Looking over your right shoulder, assessing the offender is in a radar WEZ (weapons employment zone) aft of your wing line with the ability to continue to bring his nose to bear, you will need to execute a defensive ditch. The WSO will need to check the altitude, and direct the TCC (tactical crew coordination) of "Ditch 8k to the floor." You will need to select MIL power and ease back stick pressure to transition from the deep-end of the moderate buffet to the moderate buffet, while the WSO expends flares, and roll the aircraft with lateral stick to re-orient your lift vector in slight lead of the offender. Think about putting the lift vector on an imaginary 3rd aircraft in echelon outside the turn. Then you will need to select Max-AB (after burner) and smoothly pull to the deep end of the moderate buffet. As you execute this maneuver the offender will transition from your right 4 o'clock to your left 7 o'clock and flow towards your deep-six as the offender approaches your point of departure. It is extremely important that you maintain tally of the offender throughout this maneuver, cross checking your altitude to the floor. As you transition through 90 degrees nose low, you will need to ease back stick pressure to prevent an accelerated stall. At this point you should be assessing if the offender executed an early, late, or on-time ditch follow-through..."

The above verbal description would be accompanied by the use of sticks to show aircraft positional relationships, hand-drawn two-dimensional lines (from both a "gods eye view" and "grandstand" view), and hand drawn depictions from the first-person perspective aimed at developing an accurate "picture" of what the student can expect airborne (see Figure 1).[5] The effectiveness of this instructional method relies heavily on two major factors. First, the ability of the instructor to clearly and accurately articulate the "cue." Secondly, students must be able to process the instructor's description/depiction in order to construct a visualization accurate enough to recognize the "cue" when airborne.

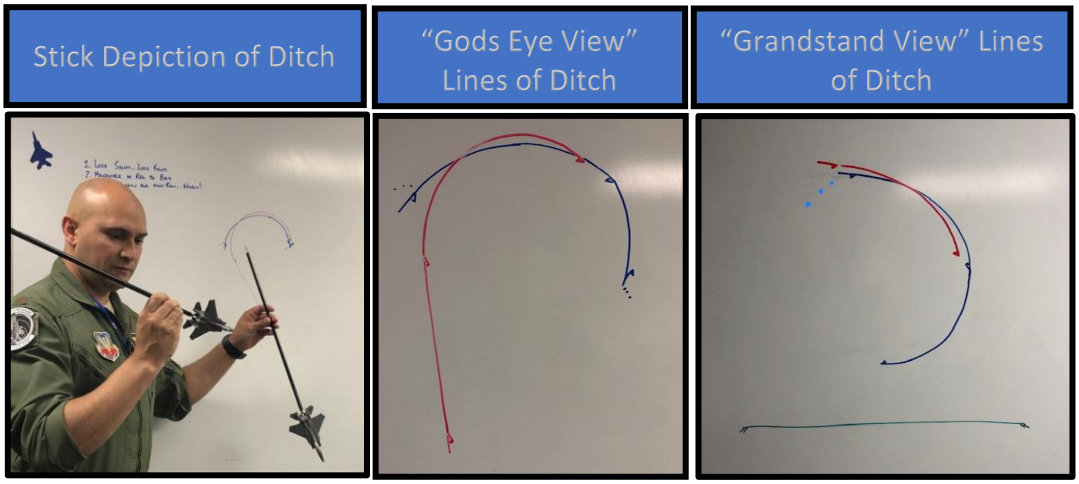

Figure 1. Example Defensive BFM Briefing Aids

Approximately an hour and thirty minutes after the conclusion of the brief, the student pilot and/or WSO will find themselves airborne at 430CAS and 3-4Gs with an offender behind them in a WEZ and hear the exhilarating phrase "FIGHTS ON!!!" It is under these conditions that the student must compare what they are seeing to their interpretation of the instructor's brief, and then execute the appropriate maneuver. Between fights, the instructors will attempt to provide brief feedback on airborne observations of the student's performance while the engagement is fresh in the student's short-term memory, but this instruction is generally limited to 2-3 key points with 15-30 seconds of instructional fixes per point.

Approximately two hours after the last airborne engagement (4-5 hours after the brief) the instructors will start the mission debrief. This is where the preponderance of learning happens in flight training. Instructors review the student's tapes (digital video recording system – DVRS) and use flight recreation software to analyze student performance and tailor instruction to the student's weakest areas. Complementing the Cue, Action, Mechanics methodology from the brief, instructors will use a Perception, Decision, Execution mantra in debrief to identify the primary cause of errors in flight performance. When determining if a perception error exists, the instructor relies heavily on pointed questions about the student's recollection of what they saw airborne. This reliance on the ability of the student to distinguish between multiple engagements (5-8 per flight) and further accurately remember specific "pictures" within the engagement being debriefed is less than ideal. It is not uncommon for the student to either respond with "I don't remember" or "I think so" leading the instructor to concentrate their instruction on the decision and/or execution when in fact misperception is routinely the causal error. When perception errors are identified, instructors will revert back to the instructional brief to remind the student of specific cues that indicate the need for a specific defensive maneuver. Current flight recreation software such as ICADS (individual combat aircrew display system) and CMDP (common mission debrief program) provide the instructor the ability to use "truth data" regarding positional relationships between aircraft to definitively determine if the appropriate cues were present, but the fidelity of these systems still requires a level of interpolation and imagination in order to be effective in recreating the actual cues (aircraft detail for range, offender nose position, wingtip vortices, line-of-sight rates, etc.) that fighter pilots and WSOs react to in flight. According to a March 2019 survey, 82% of F-15E FTU instructor pilots and WSOs respondents identified perception as the most common BFM error during IQT. Similarly, 51% identified perception as the most common student error in ACM (aerial combat maneuvering). 63% of these instructors stated that errors in inflight perception required a re-fly of the mission at least 50% of the time.[6] With this data in mind, it is logical to reassess the effectiveness of current instructional techniques designed to develop an accurate depiction on which student aircrew will be able to quickly and accurately recognize during high-G maneuvering.

Learning Theories That Apply to Basic Fighter Instruction

The current instructional methods in fighter aircrew training described above involve a mix of behaviorist and constructivist learning theories, with the predominance of behaviorist learning techniques being applied in academics and instructional briefings while flight and simulator training leverages constructivist learning. Behaviorist learning focuses on the ability of the human brain to process information in an input/output relationship. Under this approach, "learning is accomplished when a proper response is demonstrated following the presentation of a specific environmental stimulus. For example, when presented with a math flashcard showing the equation "2 + 4 = ?" the learner replies with the answer of "6." The equation is the stimulus and the proper answer is the associated response."[7] Behaviorist instructional techniques leverage the ability of the human brain to recognize commonality within generalities, and relies heavily on the ability of an individual to transfer experience between similar situations. The concept that effective instructional briefings should leverage a cue = action approach is a direct application of behaviorist learning theory, as "the goal of instruction for the behaviorist is to elicit the desired response from the learner who is presented with a target stimulus."[8] When training fighter aircrew, instructors rely heavily on the intellectual capability of the student to process the description of the cue and to build a mental model of what that cue should look like. This is where the instructional briefing approach breaks from behaviorist techniques. According to the behaviorist model, the majority of cue recognition comes from structured repetitive performance of the task with immediate feedback. The high cost of flight and simulator training prohibits full implementation of this trial and error approach, resulting in the application of both constructivism and experiential learning techniques in flight and simulator training.

Constructivism learning theory breaks from behaviorism with its heavy importance on context, whereas behaviorism focuses on generalities. According to the constructivist, "learning always takes place in a context and that the context forms an inexorable link with the knowledge embedded in it."[9] In training fighter aircrew, context is extremely important when making decisions. For example, the threat posed by an adversary may call for an exaggerated vertical maneuver to defeat their attack, but if there is not enough altitude to perform the maneuver the pilot/WSO must choose to execute a less effective maneuver so as to avoid hitting the ground. This context is lost in the behaviorism learning theory, but is crucial in fighter aircrew training.

Finally, fighter aircrew training leverages Morgan McCall's 70-20-10 theory which asserts that 70 percent of a person's learning comes from experience (doing), 20 percent from social learning (learning from other's experiences), and 10 percent from traditional academic setting.[10] McCall combines both experience and social learning into a parent classification called informal learning, while the traditional academic setting is classified as formal learning. Under this construct, flight training utilizes experiential learning through flight and simulator training, social learning through debrief and class trend analysis, and formal learning through instructional briefings and classroom academics. Unfortunately, the current construct of fighter aircrew training places over 50% of its effort in formal training.[11] Introduction of Virtual Reality into fighter aircrew training presents the possibility to augment formal training with the benefits of informal training, ultimately realigning instructional effort closer to the 70-20-10 model and increasing the instructional efficiency of the FTU enterprise.

What Is Virtual Reality, And What Tech Is Available?

The concept of virtual reality has been around for decades, but just recently has technological capability breached the price point to where VR is becoming available to the average consumer. Companies such as HTC, Oculus, Samsung, and Sony have all released consumer VR headsets under the $400 price tag. VR headsets use independent images displayed in front of each eye to create the illusion of unlimited depth, and are encased in a goggle style headset that eliminates outside light, creating an extremely immersive experience. Additionally, these headsets are accompanied by hand controllers that allow the user to interact with the virtual environment. Two to four room sensors are used to track the position of the headset and hand controllers (or additional objects) while accelerometers within the headset are able to accurately re-render the displayed image as the user moves their head.

As of February 2019, the highest resolution of generally available VR headset is the HTC Vive Pro which boasts a resolution of 1440x1600 pixels per eye with a field of view of 110 degrees and refresh rate of 90Hz. Based on the close proximity to the eye, pixel count can be deceiving. Instead, "pixel density stated as pixels per degree (PPD) is a much more useful figure, especially when dealing with AR and VR headsets."[12] Pixel density equals the number of pixels per degree of eye movement. With this calculation, the HTC Vive Pro has a 13.8 PPD. With 20/20 vision the human retina can discern the space between shapes as small as one arc-minute which equates to 60 pixels per degree, therefore the HTC Vive pro delivers approximately 1/5 the visual acuity of the naked eye.[13] In 2018, Google and LG announced the development of an OLED display with a resolution of 4800x3840 optimized for VR headsets that should deliver approximately 41PPD.[14] Further advancements in display technology are expected to result in VR display resolution approaching 60 PPD in the near future.

The introduction of affordable VR technology has created a vibrant market of VR content and software developers. VR software has leveraged video game design engines such as Unreal and Unity, maximizing interoperability of off the shelf video game accessories such as specialized controllers (joysticks, flight controls, steering wheels, etc.). This allows for a truly customized VR experience, as VR could be utilized simply as an immersive display with physical controllers/input devices (mixed reality), or for an entirely virtual experience where all interaction is done through manipulation of virtual input devices such as switches, levers, and buttons.[15] Companies such as Leap Motion eliminate the need for hand controllers by utilizing a short-wave IR camera mounted on the front of the VR headset to individually track the user's hands and fingers.[16]

One of the current major limitations of a truly immersive experience is the lack of physical sensory (haptic) feedback. This forces VR to rely heavily on visual and auditory feedback for VR interaction. Companies such as HaptX and VRGluv are focused on developing VR gloves that provide haptic feedback, but "exoskeleton" style designs based on motorized cables/pulleys make them unwieldy and cumbersome. Additional aircraft haptic feedback systems such as seat shakers and dynamic stick resistance aid in VR immersion, but still lack the precision required to consider replacement of actually flying dynamic maneuvers with a VR based simulation system.

The explosion of the VR consumer electronic market has also led to development of 360-degree cameras. Companies such as GoPro, Kodak, Nikon, and Samsung are producing high resolution (4k) cameras, allowing easy creation of VR-compatible video. Harkening back to the discussion about VR headset resolution, as headset display technology increases, so will the requirement for camera resolution. 360-degree video collection at 8k resolution and 90 frames per second will be required to prevent a reduction in quality from that observed by the naked eye.

How VR Can Change Basic Fighter Instruction

The introduction of virtual reality provides the opportunity for fighter aircrew training to blend experiential learning techniques into the current traditional cognitive approach in the academic classroom. Current F-15E Basic course involves 90 days of classroom academics before students start their flight training in the Strike Eagle. During these 90 days, students are taught aircraft systems (engines, fuels, hydraulics, flight controls, radar, targeting pod, armament, etc.) using a combination of lecture, workbook, computer-based training (CBT), and multiple-choice testing. Nearly all of these training modules require comprehension of the functionality of aircraft systems and concepts which students are unable to physically see. Current VR applications such as ShareCare VR allow the user to interact with the human anatomy by separating the skeletal, circulatory, nervous, and muscular systems with a simple gesture while further allowing the user to zoom in to observe how specific organs operate and are interconnected (see Figure 2).[17] A similar approach could be applied to aircraft systems, where the student would be able to break out aircraft systems (propulsion, electrical, fuel, hydraulic, flight control, etc.) to visually observe how these systems operate. Additionally, the ability to demonstrate systems malfunctions would allow students to fully understand aircraft emergency procedures., increasing the likelihood that they would accurately diagnose abnormal situations when airborne.

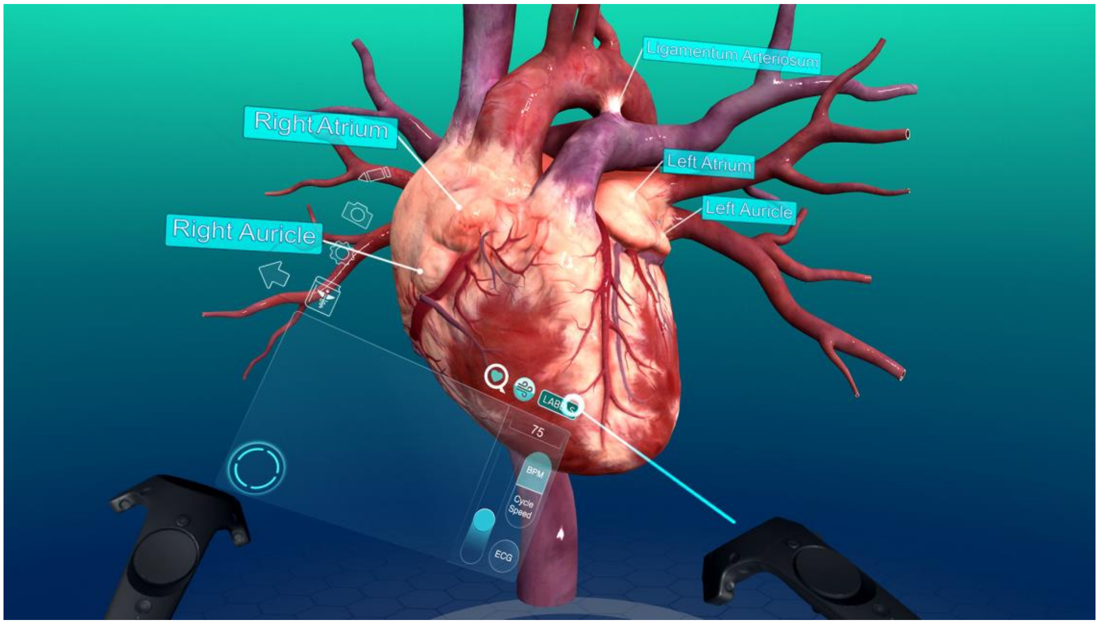

Figure 2. ShareCare VR demonstration of the human heart

Another academic application would be the development of a virtual aircraft walk around. Prior to starting the aircraft for a mission, the aircrew perform a visual inspection of the aircraft they have been assigned to fly. F-15E aircrew -1 and -34 checklists identify between 50 and 75 items (based on configuration) for aircrew to inspect before accepting the aircraft from maintenance.[18][19] IQT students receive an academic lesson followed by a hands-on group walk around on an aircraft in a hangar with an instructor. Unfortunately, this walkaround is often performed on an aircraft in good condition, forcing the students to imagine the conditions in which they would need to get corrective maintenance performed. Additionally, this same approach could be applied to pre-flight inspections of weapons loaded on the aircraft. The multitude of combinations of weapons, fuzing, and position on the aircraft is constantly challenging aircrew with new weapons preflight situations. Developing a virtual walk-around would enable aircrew to encounter aircraft and weapons with abnormalities, increasing student comfort and understanding of the aircraft walk-around and acceptance process, and further decreasing the likelihood of aircrew accepting an unsafe aircraft.

Once students progress from academic training to the flight line, the focus shifts from conceptual to functional, but the applicability of VR to increase instructional effectiveness continues. As described earlier, the intent of the instructional brief is to ensure the student has an accurate expectation of the upcoming flight and is fully prepared to successfully accomplish the tasks required for mission accomplishment. The biggest challenge in today's instructional environment is to effectively describe and display the dynamic portions of the mission accurately enough for the student to quickly recognize these "pictures" airborne. Administrative portions of flight such as formation takeoff/landing and air-to-air refueling (AAR) rely heavily on verbal description combined with 2D pictures of cockpit references to develop the appropriate mental model of what the student will experience in flight. The introduction of 360-degree video to give the students an immersive demonstration of these tasks would greatly enhance the accuracy of the students' expectations. Additionally, the use of 360-degree video as an instructional briefing aid will introduce the temporal (pacing/timing) accuracy, which is severely lacking in current methods. Formation takeoff/landing are unable to be performed in current simulators, as these systems are not modeled to display the flight lead pilot's visual signals (hand signals and head movements) required to perform these maneuvers. Additionally, the simulators are not modeled with the ability to perform AAR. The use of VR technology and 360-degree video has the potential to increase the effectiveness of formation takeoff/landing and AAR instructional briefing at a fraction of the cost of achieving equivalent fidelity in fighter flight simulators.

As student's progress into the basic air-to-air phase of training, they are exposed to aggressively maneuvering in close proximity to an adversary aircraft. Whenever maneuvering within visual range of an adversary, there are three timeless truisms known as the golden rules of BFM:[20]

1 – Lose sight, lose the fight
2 – Maneuver in relation to the bandit
3 – Trade energy for nose position wisely

These rules all center on the ability of the fighter pilot/WSO to recognize when they are being threatened by the adversary aircraft. One of the primary reasons that briefing descriptions fail to develop the appropriate visual expectation, is the fact that the size of the aircraft models, pictures, and drawings are significantly larger than what the students see when airborne. The 42-foot wingspan of an F-15E at 6000 feet is only 7 milliradians, or approximately ¼ inch wide when presented 1 yard from the eye. Therefore, the ability to accurately perceive the threat posed by the offender is currently only gained through the experience of costly ($23k/flight hour) repetition (sets). In a typical BFM mission a student is only able to perform 1-2 sets per type of engagement, rarely developing the experience to fully develop proficiency. A virtual reality headset with at least 30PPD would have the potential to accurately replicate these pictures with the detail sufficient to develop a memory from which the student's brain will be able to quickly reference airborne, therefore decreasing the amount of inflight sets required to gain this experience by supplementing with high-fidelity pre-flight study.

California based company STRIVR has leveraged VR technology to aid college and professional football teams to train, develop and prepare quarterbacks for the complex and time critical skill of reading a shifting defense. Chicago Bears quarterback Mitch Trubisky praised the effectiveness of VR in his training, "especially calling plays in the huddle — I call the play, go out and practice it, and Coach can see on the screen where my eyes are going. So, it has helped me with progression and timing without actually going onto the field and having to do it."[21] The correlation between skills required for high level performance by a quarterback and those required of a fighter pilot in BFM are surprisingly similar. A quarterback must recognize the defensive maneuvers (cue/perception), quickly identify the most likely receiver to be open based on the defense's actions (action/decision), and then accurately throw the pass to the receiver (mechanics/execution) …all while facing the consequence of bodily harm if unable to do any of these items in the allocated time. VR challenges the notion that a good QB must possess an innate quality in the untrained aspects of football, but as Baylor football coach Matt Rhule states "it's also about recognizing plays and structure, and I think instincts can be learned and taught [through VR], so that intangible things become tangible."[22] The success of VR to increase quarterback performance at both the college and professional level leads to reasonable inference of similar results in training fighter pilots in WVR maneuvering.

Similar to STRIVR's sports application of VR training, students should be encouraged to perform self-study at home in preparation for each WVR flight. This self-study should include a sort of gamification to provide students with immediate feedback of proper cue recognition and decision making. Student performance would be logged, allowing the flight instructor to tailor the instructional brief based on feedback from the self-study events. Eye tracking technology that is being integrated into newer VR headsets has the potential to monitor and record student task loading as well as airspeed/altitude crosscheck during dynamic maneuvering. With the ability to remove two (perception & decision) of the three major factors in fighter pilot performance, costly inflight instruction will be able to apply maximum focus on refining the mechanics of executing individual maneuvers. No longer should students progress through the basic air-to-air phase of IQT having failed to physically perform certain basic maneuvers (ditch, tuck-under jink, etc.) because they never properly assessed the offender.

After the completion of the basic air-to-air phase, students move on to the basic air-to-ground phase where they learn the fundamentals of air-to-ground employment of their aircraft.

This phase of training involves a significant focus on low-altitude navigation, and low-altitude weapons deliveries. The introduction of Virtual Reality to this phase would be two-fold, demonstration of proper low-altitude attack procedures, as well as validation of low-level planning. In regards to low-altitude attack demonstration, the use of 360-degree video to accurately show students proper visual cues of dynamic maneuvers in relation to the target (strafe and pop-to-LAT). Not only could 360-degree video be used to demonstrate perfect parameters and proper cross-check, but it could also be used to show how to effectively correct common errors. Similar to WVR, VR self-study would be valuable in developing students' ability to visualize proper positional relationship with the target as well as identify appropriate corrective actions for improper target alignment.

Virtual fly-through of low-altitude routes using 3D rendered satellite imagery such as the Google Earth VR application could be extremely valuable as it would not only develop a high-fidelity expectation of the upcoming mission, but also could be used to validate line-of-sight to key terrain or cultural features. During this phase, Strike Eagle aircrew train to operating in a GPS (global positioning system) denied environment which requires consistent position updates throughout the low-level mission. These updates are primarily accomplished through the air-to-ground radar and SNIPER targeting pod. Both of these methods require clear line-of-sight to the point being used as an update. Regularly, students find out airborne that many of their planned updates are obscured by intervening terrain. The ability to identify these scenarios during mission planning would greatly increase the quality of airborne low-level training by increasing the number of position updates that students are able to practice their skills on. The vast majority (81%) of F-15E FTU instructors identified low-level mission planning as the most common error affecting mission execution, with 95% attributing terrain/cultural obstruction as the primary factor in low-level attack ineffectiveness.[23] Integration of VR into low-altitude mission planning and briefing has the potential to identify these issues before takeoff, thus significantly increasing the effectiveness of low-altitude airborne training.

Not only does VR present major advantages in academic and instructional brief settings, it also presents the potential to significantly improve the effectiveness of mission debriefs. While the current debrief method of reviewing tapes/DVRS and watching 2D or 3D lines on a large-screen monitor provides the majority of information for the instructor to effectively identify student errors in mechanics, identification of perception errors relies heavily on the recollection of the student. VR integration with current TSPI (time, space, and position information) based debrief programs such as CMDP and ICADS would allow instructors to virtually transport the student back to into the air during debrief. Not only will this refresh the student's memory of the particular engagement being debriefed, but also allow the instructor to pause the virtual playback at key moments in which the student either mis-perceived the adversary, or made an incorrect decision. This increased fidelity of flight re-construction would enable instructors the ability to provide very specific instruction on how the student should prevent making the same error in the future. While the VR is unable to provide sufficient "feel" of the aircraft to truly re-fly the maneuvers in debrief, valuable instruction can be achieved through having the student verbally identify appropriate time to execute the briefed maneuvers. Finally, integration of the pilot's Joint Helmet Mounted Cuing System (JHMCS) into the 3D flight recreation software would provide the instructor with valuable data in determining if the student missed a cue based on a poor or untimely crosscheck.

Conclusion: VR Can Increase Training Quality In A Resource Constrained Environment

Analysis of flights requiring to be re-flown based on student performance known as non-effective for student non-progression (NE-SNP) since 2014 reveals that an average of 11 missions must be re-flown during the basic air-to-air phase and 10 during the basic air-to-ground phase (see Table 2) per F-15E Basic Course. Re-flying these missions adds two full days of flying per class, and costs approximately $3.58 M per year in the F-15E. Projecting similar trends (adjusted for IQT syllabus differences) across the remaining fighter fleet (A-10C, F-15C, F-16CM, F-22A, and F-35A) it is reasonable to project that over $16M is spent annually in WVR and BSA "x-rides" (see Table 3). Initial investment in VR equipment would cost roughly $50k per FTU squadron, and additional/renegotiated software design contracts would be required to achieve the level of academic to integration discussed in this paper, but the potential to increase instructional effectiveness would cost a fraction of the current annual expense of re-flying these missions. This investment would also allow students to virtually experience flight situations rarely experienced during the limited opportunities in IQT. While it would be unreasonable to expect a complete elimination of WVR and low-altitude BSA NE-SNPs, both FTU instructors as well as FTU students identify a disconnect between instructional briefing depiction and actual inflight visual cues as a major factor contributing to poor student performance.[24] If the integration of VR technology were to eliminate half of the NE-SNPs (a conservative estimate based on FTU survey responses) not only would the FTU syllabus become more efficient, but would also present an annual savings of approximately $8M across the USAF fighter fleet.

Year	B-Course Class	NE-SNPs (BSA A/A)	NE-SNPs (Low-Alt A/G)
2014	14-ABE	5	5
	14-BBE	3	11
	14-CBE	2	3
	14-DBE	12	4
2015	15-ABE	8	9
	15-BBE	11	3
	15-CBE	8	7
	15-DBE	7	4
2016	16-ABE	8	12
	16-BBE	11	13
	16-CBE	6	14
	16-DBE	17	11
2017	17-ABE	20	12
	17-BBE	14	24
	17-CBE	14	12
	17-DBE	20	16
2018	18-ABE	7	5
	18-BBE	18	16
Average		**10.61**	**10.05**

Table 2. 2014-2018 F-15E B-Course Flights Failed for Student Performance[25]

Aircraft MDS	Re-flown sorties per class	Classes per year	MDS cost per hour	Annual Re-fly Cost (2-Ship required)
A-10C	7	4	$5,944	$332,864
F-15C	10	4	$23,124	$1,849,920
F-15E	21	4	$21,301	$3,578,568
F-16	15	8	$8,278	$1,986,720
F-22A	10	4	$33,538	$2,683,040
F-35A	7	20	$28,455	$5,691,000
Total				**$16,122,112**

Table 3. Projected Annual Re-fly Cost by MDS[26]

As this paper has described, introduction of VR instructional techniques has the potential increase student comprehension by expanding experiential and constructivist learning from the aircraft and introducing these aspects into the classroom and briefing room. The ability to visually demonstrate the operation of aircraft systems in a VR immersive environment would significantly increase the effectiveness of the baseline academics, while high-fidelity immersive visualization of complex WVR and BSA maneuvers would truly allow instructors to lead students through an immersive chair-fly of the mission, and the ability to accurately recreate the mission in debrief will undoubtedly increase the effectiveness of fighter aircrew instruction in basic phases of initial qualification training. This increased effectiveness presents the potential to reduce the requisite time in academics and decrease the required number of re-flown missions due to student performance, ultimately increasing syllabus efficiency.

As discussed at the beginning of this paper, the FTU enterprise is being strained in two polar-opposite directions. On one hand the USAF's fighter aircrew manning crisis will continue to demand increased production of fighter FTUs, while on the other hand increasing military capability of nations such as China and Russia demand that FTUs produce pilots/WSOs with increasingly complex skills. This paper has described multiple areas in which VR can increase the efficiency of FTU production. While the ability to reduce the FTU production timeline by 2-3 days will not appreciably increase the annual capacity of the FTU to produce IQT pilots/WSOs, the increased efficiency could allow the FTU to use the flight training previously allocated to NE-SNPs to introduce students to the more advanced tactics that will be required to support the 2018 National Security Strategy which directed a shift towards military preparation for great power competition.[27]

Notes

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List of Terms

Bandit –	Enemy aircraft
Ditch –	Three-dimensional maneuver in which the defensive aircraft aggressively descends 4-5 thousand feet.
Floor –	Pre-determined Mean Sea Level (MSL) altitude that aircrew establish to simulate the ground. Unlimited air-to-air maneuvering requires a floor to be established no less than five thousand feet above the average terrain.
Moderate Buffet –	Term referring to F-15E aircraft feel indicating maximum turn rate with minimum turn radius.
Lift Vector –	Term referring to an imaginary line drawn perpendicular to the wings originating from the center of the aircraft's fuselage.
Echelon –	Aircraft formation in which all wingmen are on the same side (right/left wing) of flight lead.
Deep-six –	Term referring to a position directly behind the aircraft.
Tally –	Tactical crew coordination term meaning that the aircrew (pilot, WSO, or both) visually see the bandit
Accelerated Stall –	Flight situation in which the aircraft's wing is unable to produce enough lift to maintain level flight.
CAS –	Calibrated air speed
G –	Gravitational Force
Engagement –	Term referring to an air-to-air or surface-to-air fight. In training these fights are identified by the time between "Fight's On" and "Knock-it-off" or "Terminate"

Line of Sight –	Term referring to bandit movement within the aircrew's visual field.
Line of Sight Rate –	Speed at which the bandit moves within the aircrew's visual field.
Gamification –	Inclusion of game-design elements and principles in non-game contexts.
Crosscheck –	Term referring to systematic and repetitive process in which aircrew collection of information and situational awareness from visual references and aircraft displays.