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A MULTI-YEAR STUDY OF THE SAFETY AND TRAINING IMPACTS OF INTRODUCING THE LIVE, VIRTUAL, CONSTRUCTIVE TRAINING STRATEGY INTO NAVY AIR COMBAT

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In the Navy's proposed *Live, Virtual, Constructive (LVC)* training system, virtual entities that represent pilots in flight simulators and computer-generated constructive entities will be injected into the cockpits of F/A-18 aircraft during live-flight training. The Navy expects LVC to ameliorate many of the economic and environmental impacts of live-flight training and to support future training requirements. However, the potential impact of LVC on training effectiveness and safety is not completely understood. While the naval air combat training system is notably robust, its inherent complexity precludes a straightforward analysis of potential hazards and mitigations. Two years ago, researchers began to identify and assess the numerous human-technology interactions that will characterize the future LVC training system, most notably those that could lead to hazardous LVC training situations. They employed cognitive task analysis methods to interview fighter pilots, F/A-18 weapons systems officers, range training officers, and modeling and simulation subject-matter experts (SMEs). The present paper is a follow-up to their 2013 ISAP presentation on potential LVC training hazards and mitigations identified during Cycle I of their iterative research. An additional two-year cycle of data collection, analysis, and SME review has led to an enriched understanding of the potential training hazards and benefits that could arise from interactions among training system elements. The long-term goal of this research is to develop requirements for the Navy's LVC training system that will enable its safe implementation and eventual optimization. With that goal in mind, the findings from Cycle II are presented here.

A number of economic and environmental challenges threaten the attainment and maintenance of air combat readiness. To mitigate these challenges, the Navy seeks to create a *Live, Virtual, Constructive (LVC)* training system to train F/A-18 pilots. The proposed system leverages advances in high-speed datalink technology to inject virtual tracks (tracks representing aircraft flown by pilots in simulators) and constructive tracks (tracks representing computer-generated aircraft) onto the radar and sensor system displays of live F/A-18 aircraft. In the future, the Navy plans to extend this capability to other platforms.

The naval air combat training system is a highly complex and nuanced product of decades of evolution. The introduction of LVC, a complex simulation system, into the already complex Navy air combat training system carries a heightened risk of induction of unanticipated interactions between elements of both systems, which could result in unforeseen and potentially hazardous emergent system behavior. Two years ago, Office of Naval Research-funded research began to identify and assess the numerous human-technology interactions that will characterize the Navy's future LVC training system, most notably those that could lead to hazardous LVC training situations. The result of the first yearlong cycle of data collection, a preliminary list of potential LVC training hazards, was presented at the 2013 International Symposium on Aviation Psychology (Sherwood et al., 2013). An additional two-year cycle of data collection, analysis, and subject-matter expert (SME) review has led to an enriched understanding of the potential training hazards and benefits that could arise from interactions among training system elements. This paper presents the results of the Cycle II analysis.

Method

Participants

Researchers interviewed 31 participants over the course of the study. The participants' diverse backgrounds provided insight into the potential impacts of LVC from a variety of perspectives.

Cycle I (*n* = 22). The Cycle I participants included twelve Navy pilots, one Marine Corps pilot, one active-duty Air National Guard pilot, and six retired Air Force and Navy pilots [including one who also served as an Naval Flight Officer (NFO)]. Other participants included one active-duty NFO and one active-duty F/A-18 weapons system officer (WSO). The researchers also interviewed two military modeling and simulation (M&S) experts. However, the M&S experts are not included in the participant count.

Cycle II (*n* = 9). The Cycle II pilot participants included six Naval Strike and Air Warfare Center (NSAWC) instructor pilots, one of whom was also an experienced Range Training Officer (RTO), and one adversary pilot. The participants reported an average of 2,330 flight hours in high-performance jet aircraft and flew one or more of the following fighter platforms: the F/A-18 ($n = 6$), F-16 ($n = 1$), F-14 ($n = 1$), F-5 ($n = 2$), and Hawker Hunter ($n = 1$). Other participants included a NSAWC WSO instructor and an Air Intercept Controller (AIC) who also has experience as an RTO.

Data Collection

Researchers briefed participants on the LVC training concept, the Navy's goal of using the system to improve training efficiency and to virtually extend training ranges, and the purpose of the interview. The purpose of the interview was to identify potential *training concerns* (potential negative interactions between LVC technology and current training practices), *training benefits* (opportunities for LVC to enhance or supplement current training), and *training hazards* (potential impacts of LVC on training safety if it were implemented in the existing air combat training system without mitigation). Researchers asked participants to discuss potential strategies for the mitigation of identified hazards and training concerns and to suggest ways in which LVC could optimize training. The researchers obtained permission to audio record and transcribe 21 of the Cycle I interviews. Audio recording was not permitted during any of the Cycle II interviews. However, researchers took detailed notes and gave interviewees the opportunity to review the notes and to offer corrections.

Cycle I. During Cycle I, researchers interviewed the majority of participants using an adaptation of the Critical Decision Method (Klein, Calderwood, & MacGregor, 1989). The thematic analysis of the Cycle I interview data yielded a list of potential LVC training benefits, training concerns, and—the focus of this paper—training hazards. Three researchers then jointly organized each hazard into overarching hazard categories according to the fundamental underlying interviewee concerns that they represented. All identified potential hazards were subjected to a 2.5-hour group critique and to a review by two Navy air combat experts, who commented and elaborated on the presented hazards and their supporting data. For a more thorough account of Cycle I data collection and analysis, see Sherwood et al. (2014a, 2014b).

Cycle II. During Cycle II, researchers used a semi-structured interview approach to elicit knowledge from experienced Navy air combat pilots and exercise management personnel. The goal of this data collection was to expand and refine the list of potential training benefits, concerns, and hazards identified during Cycle I.

Researchers interviewed Cycle II participants in sessions that ranged from 30 minutes to 1.5 hours. During each session, a researcher and a naval air combat SME posed a series of questions to a participant based on previously identified training hazards, concerns, and benefits, specifically in relation to training fidelity. However, the findings of the fidelity survey are beyond the scope of this paper except for instances where low fidelity could give rise to hazardous training situations.

Data Analysis

Coding of Cycle II interview notes. While researchers coded the Cycle I interview data using a bottom-up approach, they coded the Cycle II interview data using a top-down approach with respect to the training concerns, benefits, and hazards that emerged from the Cycle I interview data. Two researchers reviewed the interview notes to identify statements made by participants about the previously identified hazards and their mitigation. The researchers then assigned these interviewee statements, referred to as *data extracts*, to their appropriate hazard codes. The wording of the hazards and the organization of the hazard categories evolved over the course of Cycle II as a result of this elaboration. Table 1 lists these changes.

Safety risk level evaluation. After the coding of all the data extracts addressing potential LVC training hazards, the two researchers used the severity and probability scales of the Navy's Operational Risk Management (ORM) system to independently assess the safety risk level associated with each hazard (Department of the Navy, 2010). The researchers based their assessments on the content of the data extracts.

Researchers gave severity and probability ratings for each hazard on four-point scales. They then merged the ratings in accordance with the ORM process to obtain a risk assessment code (RAC), which represents the level of risk associated with a hazard and is expressed as a single Arabic number from 1 (critical) to 5 (negligible) (Department of the Navy, 2010). Researchers calculated three RACs for each hazard: the *baseline risk level* (the risk level of the hazard in the current live air combat training environment), the *unmitigated risk level* (the risk level of the unmitigated hazard in the LVC training environment), and the *residual risk level* (the risk level of the mitigated hazard in the LVC training environment). Researchers assessed inter-rater agreement using a linear weighted kappa, which indicated a very good level of agreement ($\kappa = 0.81$, 95% CI: [0.73, 0.89]). However, the researchers still met to reconcile any disagreements on the baseline, unmitigated, and residual risk levels. They assigned risk levels to each hazard category based on the risk levels of its component hazards. When a hazard category contained hazards of more than one risk level, researchers assigned the category the highest applicable risk level.

Results and Discussion

Researchers grouped 49 identified hazards into five overarching hazard categories: (1) Within Visual Range (WVR) Operations, (2) Human-Machine Interface (HMI) in the Cockpit, (3) Fidelity, (4) Exercise Management, and (5) Cockpit Technology. Table 1 compares the results of the Cycle I and Cycle II hazard analyses, and a summary of each Cycle II hazard category follows. Each summary includes a description of the specific hazards within a category and, as applicable, relevant mitigations suggested by interview data.

Table 1.
Results of the Cycle I and Cycle II Hazard Risk Level Analyses.

Cycle II Hazard Category	Projected Change in Hazard Exposure (Baseline vs. Unmitigated)	Unmitigated RAC	Residual RAC (Mitigated to Baseline?)	Corresponding Cycle I Hazard Categories	Projected Change in Hazard Exposure (Baseline vs. Unmitigated)	Unmitigated RAC
WVR Operations	Increase	1	1 (No)	Unseen Aircraft WVR	Increase	1
HMI in the Cockpit	Increase	1	2 (No)	Inadequate Support for HMI	Increase	2
Fidelity (Live, VC, Display, Environment, and General)	Increase	1	3 (Yes)	Reduced Big Picture Awareness	Increase	3
				Unexpected VC Behavior	No Change	2
				Complacency / Risk-Taking	No Change	2
				Negative Transfer of Training to the Operational Environment	No Change	4
Exercise Management	No Change	1	1 (N/A)	Inadequate Support for Exercise Management	No Change	3
Cockpit Technology	No Change	3	3 (N/A)	Inadequate Support for HMI	Increase	2

Within Visual Range (WVR) Operations

The opinions of interviewed pilots diverged on whether VC aircraft should go to the merge (i.e., dogfight) with live aircraft. Whether future air combat training rules permit VC aircraft to merge with live aircraft remains to be seen, but either case presents its own safety challenges to be mitigated.

Some pilots opposed to the use of VC aircraft WVR asserted that it would provide poor training, while others said that it would increase the risk of midair collision if a live pilot were to merge with a mixed group (a group containing both live and VC tracks). If future LVC training rules do not permit VC aircraft to operate WVR, VC tracks must be safely cleared from radar and cockpit sensor system displays before the merge. Since VC tracks will not likely be differentiated from live tracks on pilot displays, a sudden, unexpected disappearance of VC tracks could induce pilot confusion and attentional tunneling because there are reasons that live aircraft disappear from radar (e.g., maneuvering, accidents, and electronic attacks). Thus, pilots could end up tunneling on their radar or their out-the-window view while trying to locate the dropped “live” track that is not really there. For this reason, some interviewees suggested that, if exercise management personnel clear VC tracks (from all cockpit displays) before the merge, their action should be accompanied by a comm call indicating that VC tracks have been cleared. Interviewees also suggested that, instead of disappearing, VC tracks should turn away before they reach 10–30 nm.

Interviewees who supported the use of VC aircraft WVR felt that going to the merge with aircraft that one cannot see is good training, as pilots cannot always visually identify (VID) the F-5s flown by live adversary pilots. Therefore, while pilot failure to VID a VC track might result in attentional tunneling, the associated risks are no different from what pilots currently face in live air combat training exercises. Thus, many interviewees believed that a “merging with VC” radio call from the RTO would be all the mitigation that is needed and that, otherwise, the Navy’s current air combat training rules and procedures are resilient enough to allow for the safe operation of VC aircraft WVR of live aircraft. However, some pro-merge pilots tempered their support with the suggestion that mixed groups should be kept from the merge because of a perceived increase in the risk of pilots losing track of live aircraft and the resulting increased potential for collision. Merging with VC-only groups mitigates this risk. According to one participant, skills that could be practiced in WVR with a VC entity include merge geometry, look up, look down, time out, and weapons employment. He noted that, while a pilot would lack visual look out and some merge look out, “the goods outweigh the ‘others.’”

Human-Machine Interface (HMI) in the Cockpit

To safely conduct LVC air combat training, a number of cockpit HMI design challenges must be resolved. One challenge is to design a solution to address situations in which a pilot must know which aircraft are live. For example, they may become cognitively overloaded and lose situation awareness (SA), or a training incident or accident may occur. Based on participant input, the solution could take the form of either an ever-present, unique VC symbol set or a pilot-controlled switch to clear VC aircraft from cockpit displays. However, most interviewees opposed the artificiality of unique VC symbols (often citing the aphorism that one must “train as you fight”). The use of a pilot-controlled switch to remove VC tracks temporarily met wider support, perhaps in part because the removal of tracks from cockpit displays is not a significant departure from the current training procedure. “If a young guy is overwhelmed, he can currently do this,” noted one interviewee. “Leaving the VC entities off for a period of time is okay. We do that currently with the MIDS/Link-16 display.” Moreover, since the LVC-off switch would be intended for use by “overwhelmed” pilots or during emergency situations, it must be designed so that a single-seat F/A-18 pilot can operate it without increasing his or her cognitive load or further degrading his or her SA. More specifically, the switch must be readily available and consistently function in the same way, regardless of aircraft mode.

Interviewees expressed an additional concern: ensuring clear indications of the operational status of the live and VC track data feed(s), particularly if VC tracks are sent through a separate data feed. In this case, it is possible that a pilot’s Link-16 (i.e., the live track feed) could fail and the VC tracks populating the displays could camouflage the problem. However, this scenario is very unlikely, as pilots already have a clear indication of a lost Link-16. A similarly clear indication of status of the VC track feed should be provided so that pilots’ SA is not disrupted by VC tracks unexpectedly disappearing and reappearing. Finally, the LVC-enabled cockpit should support LVC mode awareness. Pilots need to be aware of whether their systems are in LVC training mode or operational mode. Although unlikely, it is possible that pilots could mistakenly enter operational mode and thus could misinterpret information, treat a live aircraft as VC, or take the wrong action for a given context.

Fidelity

Potential fidelity concerns in the LVC environment include the disparate speeds and capabilities of simulated, state-of-the-art adversaries and live F-5 adversaries; the potential for VC tracks to be fed into cockpit displays in ways that do not realistically simulate sensor system noise, ambiguity, and inaccuracy; imperfect correlation of VC behavior across sensor system displays or displays that are out of sync with a pilot’s offensive and defensive actions against a VC adversary (e.g., failure to accurately portray broken radar lock); and unexpected VC track behavior.

During training, exercise participants could become cognitively fatigued because of the extra work required to perceive, synthesize, and make sense of unrealistic and imperfectly correlated sensor system data. Fatigued pilots are more likely to make mistakes, lose SA, or exhibit reduced flight discipline. Furthermore, unexpected behavior by VC entities could distract, confuse, or cause a pilot to maneuver reactively. All these factors increase the possibility of a midair collision with a wingman or other aircraft. In the case of "cognitive overload caused by LVC training artificialities, a pilot may use the proposed "clear VC" cockpit switch to regain his or her SA. However, interviewees proposed a number of solutions to prevent pilot SA from being degraded in the first place. For example, the disparity between advanced VC adversaries and live F-5s could be masked or avoided in multiple ways. First, VC tracks could be overlaid on live tracks so that pilots receive both VC indications and live electronic attack (EA) capabilities. Second, VC and live tracks could be blended in the tactical combat training system (TCTS) and then fed to the live aircraft. In this case, radar would be turned off when LVC is on and adversaries are beyond visual range (BVR). Finally, if other interventions do not prove sufficient to compensate for VC artificialities, VC tracks could turn away before the merge, and/or merging with mixed sections could be prohibited.

In addition, LVC artificialities must not impair skills or produce mindset changes that can be carried into combat. Poor VC adversary and sensor system fidelity could ultimately result in pilots and E-2 NFOs going into combat without sufficient training on enemy tactics and perception and coordinated interpretation of multiple sensor system displays, leading to preventable casualties. To increase LVC sensor system fidelity, the LVC system should allow instructors to vary radar strength, clutter, and EA. Furthermore, it should allow instructors to tie VC tracks to live tracks. The live tracks would be detected and tracked by radar, and later, after the adversary section was much closer, the VC entities would break out as separate tracks.

Exercise Management

The addition of VC aircraft to the air combat training environment will increase the workload and complexity of exercise management. The high workload associated with the control of less-intelligent constructive entities is of particular concern, and the task of managing these tracks will likely need to be divided amongst a number of exercise managers depending on the size of the exercise and the availability of work support tools to make the task easier. Otherwise, if overextended, managers could fail to notice and mitigate hazardous conditions or make changes to VC adversary behaviors or plans that are not sufficiently thought out, potentially causing confusion for live pilots. Moreover, additional exercise management roles might need to be created to control the VC entities effectively and to ensure that training rule violations and hazardous situations are detected by managers just as easily as in current, all-live training exercises. The key problem, however, with the creation of additional exercise management roles may be finding the balance between having enough managers to distribute the workload effectively and having too many managers so that it becomes impossible to maintain intra-team communication during time-pressured situations, thus affecting team SA and reducing the managers' ability to identify and address potentially hazardous training situations. As one interviewee put it, "There is a point of diminishing returns. Someone—one person—has to be the bubble and decision-making authority. Too many people is not good."

Cockpit Technology

The LVC architecture must not create a security weakness in network or onboard systems. Furthermore, there are various potential hazards associated with the LVC architecture that depend on its level of integration with the F/A-18 Operational Flight Program (OFP). Architectural options include (a) feeding VC entity data to separate LVC system displays, (b) feeding VC entity data through the same datalink as live track data to appear together on existing cockpit displays, and (c) feeding live track data to LVC training system computers, which, in turn, would feed VC and live tracks to existing cockpit displays.

If the LVC architecture is fully integrated with the OFP, the fusing of VC entities into track files carries the risk that the multi-sensor integration (MSI) function might mis-correlate live track radar data with VC track data. Although unlikely, this includes the possibility that exercise interlopers (e.g., white air and other "non-squawkers") could become correlated with a VC track occupying the same airspace. "F-5s fly around in the FRTC (Fallon Range Training Complex) without radars all the time. I won't see you anyway," said one interviewee, implying that interlopers are not a significant concern. This pilot went on to suggest that, "if feeding a TCTS feed, [exercise managers] could generate… a 'safety' track file [that would represent non-participants in the training arena]. A good guy on the console (the RTO) will handle it." Conversely, if LVC is not fully integrated into OFP displays, possible hazards could include the increased risk of training accidents because of (a) the increase in cognitive workload required to reconcile OFP displays with LVC displays; (b) the potential for pilots to focus on the LVC displays, thus missing safety-critical data on the OFP displays; and (c) the potential for pilots to use the separate displays to game the system (e.g., to shoot live aircraft first), which might encourage pilot complacency and risk-taking.

In addition, the LVC architecture must prohibit the inadvertent launch of live weapons when the system is in LVC mode. The OFP should prevent pilots from accessing LVC functionality if active weapons are loaded. However, the datalink(s) used during LVC exercises could provide an additional safety net against accidental live fire. “Certain datalinks don’t let you send data unless it’s valid data. So data associated with intent to fire when an aircraft has live ordnance on board could potentially be blocked, preventing a live launch,” according to an air intercept controller (AIC) interviewee.

Discussion

In the coming year, additional data collection, analysis, and SME-review will take place as needed to further elaborate upon the identified hazards. Using risk analysis to prioritize potential LVC safety hazards, researchers created a roadmap created for these efforts, which will focus on identifying the most promising mitigation strategies. The mitigation of potential LVC training hazards associated with WVR operations, cockpit HMI, and training fidelity should be given priority, as they represent the largest potential increases in pilot risk exposure relative to current all-live training. In addition, further research is needed on the potential effects of LVC on exercise management team SA, communication, and coordination to determine what work support tools and/or additional roles should be created to mitigate the increase in workload caused by the addition of VC entities. The long-term goal of this research is the development of requirements for the Navy’s LVC training system that will enable its safe implementation and eventual optimization.

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