Neuroergonomic Assessment of Simulator Fidelity in an Aviation Centric Live Virtual Constructive (LVC) Application

Tom Schnell[1], Alex Postnikov[2], and Nancy Hamel[3]

[1] Operator Performance Laboratory (OPL), University of Iowa, Iowa City, Iowa, 52242, USA
[2] Advanced Technology Center, Rockwell Collins, 400 Collins Rd.,
Cedar Rapids, IA 52498, USA
[3] Advanced Infoneering, Inc., 433 Hwy 1 W, Iowa City, IA 52246, USA
thomas-schnell@uiowa.edu, apostnik@rockwellcollins.com,
nhamel@advancedinfoneering.com

Abstract. This paper describes a recent human factors study that was performed on a flight simulator and in a fighter trainer jet aircraft to quantify the cognitive effects of simulator fidelity. There are many parameters that could be manipulated to affect physical fidelity in a simulator and we want to point out that in this study we make no claims of having covered a large portion of the possible fidelity design space. Rather, this study provides a comparison of trainee performance in a low to mid-level simulator with the performance obtained in a real fighter jet training aircraft using state-of-the-art operator state characterization equipment. As this study is ongoing, only partial data is shown in this paper.

Keywords: Neurocognitive measures, operator state characterization, flight training.

1 Introduction

This paper describes a human factors study, which was funded by the Office of Naval Research (ONR) as part of a Small Business Technology Transfer Research (STTR) program at Advanced Infoneering, Inc. [1]. The study involved the measurement of neuroergonomic parameters including eye gaze behavior, electroencephalogram (EEG), heart rate variability (HRV), and mission specific measures of performance in pilots performing a close air support (CAS) task using a pop-up bombing maneuver in a simulator and a real fighter jet trainer aircraft.

The technology that was developed under this STTR will find application in civilian and military flight training and technology testing applications. One application that is especially well-suited for neuroergonomic performance assessment technology is the emerging area of Live Virtual Constructive (LVC) training. LVC is a relatively new paradigm in aviation training that has considerable potential to revolutionize the way aviators are trained and prepared for their missions. LVC incorporates live aircraft, virtual simulators, and constructive entities into a single

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environment that provides training participants with an opportunity to interact the same way how they would interact when performing their real missions in theater. Live aircraft are connected to the network of ground-based simulators using high-bandwidth digital datalinks and dedicated robust data protocols [2]. In this fashion, LVC not only supports the training of the pilots in the live aircraft and flight simulators, but also the training of other participants, such as airborne and ground-based controllers and their support teams including Joint Terminal Attack Controllers (JTACs) and Joint Forward Observers (JFOs). Rockwell Collins in collaboration with the Operator Performance Laboratory (OPL) recently demonstrated the huge training potential of LVC by enabling a real JTAC to receive LVC training to regain night currency during a demonstration at the 2010 Interservice Industry Training Simulation Education Conference (I/ITSEC) in Orlando [3]. During this training for credit, the JTAC in training controlled the OPL jet aircraft flying in Iowa. From this JTAC training station in Orlando he prosecuted a simulated close air support mission against virtual targets that were overlaid in the real world.

Naval aviation flight training is performed using a combination of procedure trainers, flight simulators and live aircraft [4]. While flight simulators and procedure trainers have become very capable and flexible, there are still many skills that naval aviators need to acquire in live training and fleet aircraft. However live flight training can be very costly and logistically difficult to accomplish and the current fleet of aircraft is fairly thinly stretched across training and war fighting operations. LVC is an integration concept that incorporates live, virtual, and constructive elements into a single environment, in an attempt to leverage the best of each world to minimize logistics and maximize training effectiveness [2, 5]. What makes LVC so attractive is its ability to connect airborne and ground-based assets in a net centric training exercise that can be geographically distributed [6].

The overarching objective of LVC training is to improve the effectiveness of the delivery of content while at the same time achieving a reduction in operational costs and enhanced flight safety. Cost-effective delivery of instruction will be enabled by the inherently embedded and net centric capability of LVC [2, 5], where the reduction is demonstrated by a smaller number of training flights required to complete the tactical tasks and component skills called for in the training syllabus and also through a reduction in the required number of flights to provide live opposing force necessary for readiness training of another pilot [7]. LVC also requires the development and indoctrination of new concepts of operation (CONOPS) including methods of exercise planning, briefing, air traffic and range control, rules of engagement (ROE), handling of emergencies, performance evaluation, and debriefing. Our team has performed LVC research and demonstrations for the past two years [2, 6], and we feel that LVC has great potential to reduce cost by reducing or eliminating logistical complexities and enhancing training effectiveness by enabling early immersion of trainees in complex net centric distributed exercises that draw on many dimensions of the cognitive-perceptual stimulation that is necessary to prepare our warfighters for effective operation in theater.

Designers of virtual environments such as flight simulators are faced with difficult cost-benefit trade-offs that may affect its fidelity and its training effectiveness or transfer of training. The construct of fidelity has several dimensions, including physical fidelity, functional fidelity, and cognitive fidelity. Interaction of different fidelity dimensions have an impact on trainee immersion, presence, and buy-in [8]. In flight simulators, physical fidelity relates to the accuracy of the physical layout of the crew station and how closely the visual, auditory, haptic, vestibular, and flight dynamic stimuli mimic those that will be experienced in the real aircraft. Functional fidelity primarily relates to how accurately the simulated crew station equipment acts like the operational equipment and cognitive fidelity is a quantification of how closely the human factors effects of the virtual environment track with those that will be found when training in the real aircraft.

This paper describes the synergistic combination of our recent developments in aviation LVC technology in conjunction with a human factors study to specifically investigate the cognitive effects of simulator fidelity. The Operator Performance Laboratory (OPL) has two L-29 jet training aircraft [6], each modified with an evaluation cockpit in the rear seat, integrated instrumentation pods, a ground support infrastructure, and a neuroergonomic operator monitoring and evaluation system [9, 10]. Additionally, the OPL has developed a matching ground simulator with a functionally identical simulated avionics set up and the same operator monitoring system. The avionics, datalink, and LVC concept of operations work at OPL was funded over the past two years by Rockwell Collins.

2 LVC Research Apparatus

Our current LVC infrastructure consists of two L-29 jet training aircraft (Fig. 1) and two flight simulators, one being of a fast jet factor and the other one being of a transport aircraft form factor. Each aircraft is instrumented with an evaluation cockpit in the rear seat, integrated range instrumentation pods, a ground support infrastructure, and an operator monitoring and evaluation system. A third, piston powered, aircraft is available for use as data link relay and/or as an airborne command-and-control platform. The flight test assets are interconnected to a ground station using a range instrumentation, datalink that can transmit in several formats, including the Advanced Range Data System (ARDS) protocol. A command-and-control ground station with two high gain pan-tilt rotator systems is located at the OPL flight operations center at the Iowa City municipal airport. This ground station provides the interconnection between the airborne and ground based assets. All ground assets communicate with each other using the HLA protocol. By using this constellation of airborne and ground-based assets, we can test the performance of multiple crews in an LVC exercise.

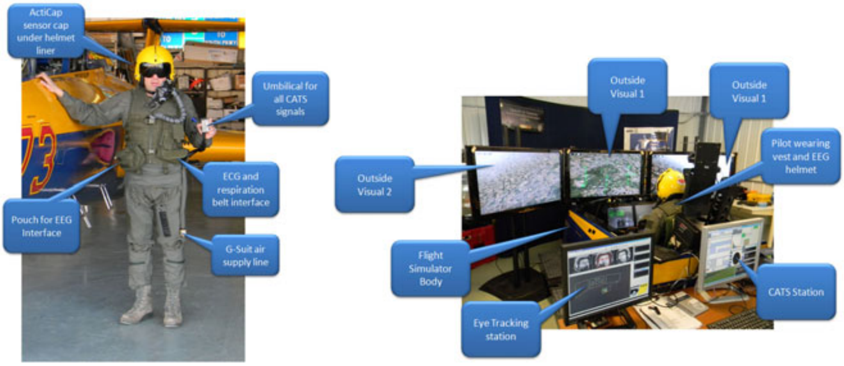
To simplify the deployment of the neurocognitive and physiological sensors on the pilot we have integrated the EEG electrodes in the liner of a flight helmet. The respiration belt and ECG electrodes are worn under the flight suit connecting to the peripheral electronics that are integrated in a pilot survival vest as shown in Fig. 2a. This level of integration provides for a ruggedized instrumentation package with a single point umbilical connection to the aircraft or flight simulator. Fig. 2b shows a rear quartering view of the fixed base flight simulator that was used in this study. The flight simulator features three channels of outside visuals, subtending a total of 135° lateral visual field of view (FOV) or around 45° per channel and a vertical field of view of 25 degrees. The outside visual (OSV) channels 2 and 3 were used to manipulate the fidelity of the flight simulator with low fidelity corresponding to the condition where OSV 2 and 3 were off and medium fidelity when OSV 2 and 3 were on. In the present study, high fidelity corresponded to runs in the L-29 jet.

Standard F/A-18 head up display (HUD) symbology was overlaid on OSV channel 1, providing the participant with symbology to fly a bombing run with a Continuous Computed Impact Point (CCIP) for Mark-82 dumb bombs. The head-down display (HDD) showed the layout of an F/A-18 instrument panel with Stores Management System (SMS), map page, Up Front Controls (UFC), and a Horizontal Situation Indicator (HSI) page. The HDD is a touch screen so that all SMS and UFC functions can be activated by touch.

Hawk 11 Hawk 12 Range Integration Pod

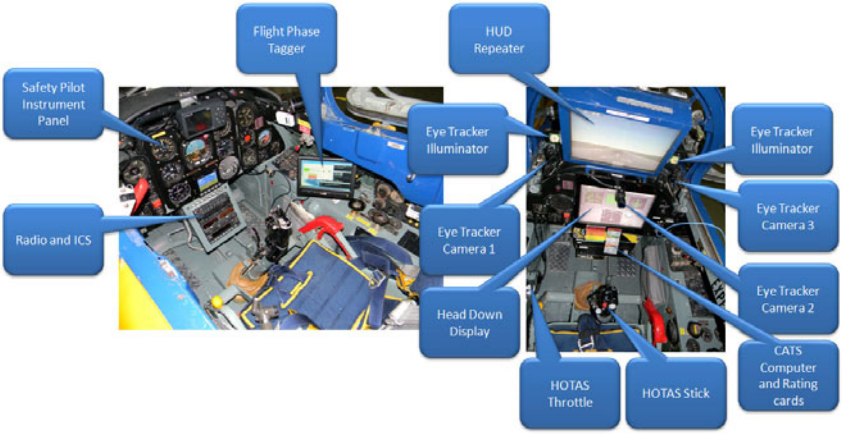
Fig. 1. OPL's Instrumented L-29 Fighter Jet Trainer Aircraft

Fig. 2c shows the front cockpit of the L-29 jet where the safety pilot (SP) operates. The SP performs all maneuvering on the ground, take-off, landing, and repositioning of the aircraft between runs. The SP uses standard aircraft instruments to navigate in US airspace under FAR part 91 flight rules. Two VHF radios are available to allow the SP to simultaneously communicate with air traffic control (ATC) and the command and control ground station on separate frequencies. A side display touch screen called the Phase Tagger (Fig. 2c) is available to the SP to start and stop the recorder, tag events to check the video data link integrity, and to check CATS and the integrity of the eye tracker. The rear cockpit is the crew station that the evaluation pilot (EP, experiment participant) occupies. A daylight readable 15 inch touch screen display installed in the head-down position that allows presentation of any avionics symbology as per program requirements. The symbologies can be driven either with PC board dedicated avionics graphics processors. In this experiment, the symbologies were identical to the ones used in the simulator and represented an F/A-18 instrument panel. A daylight readable 15 inch touch screen in the head-up display (HUD) position provided the same outside visuals and F/A-18 HUD symbology as in the simulator. The lateral FOV of the HUD display was 45° which made the imagery displayed on it conformal with the real world. Therefore, a pilot in the rear crew station had an essentially unrestricted view of the surroundings, with the central 45° being a computer generated photorealistic inset and the remaining view being the real world.



a. Pilot with Sensor Vest

b. Flight Simulator



c. L-29 Front Cockpit

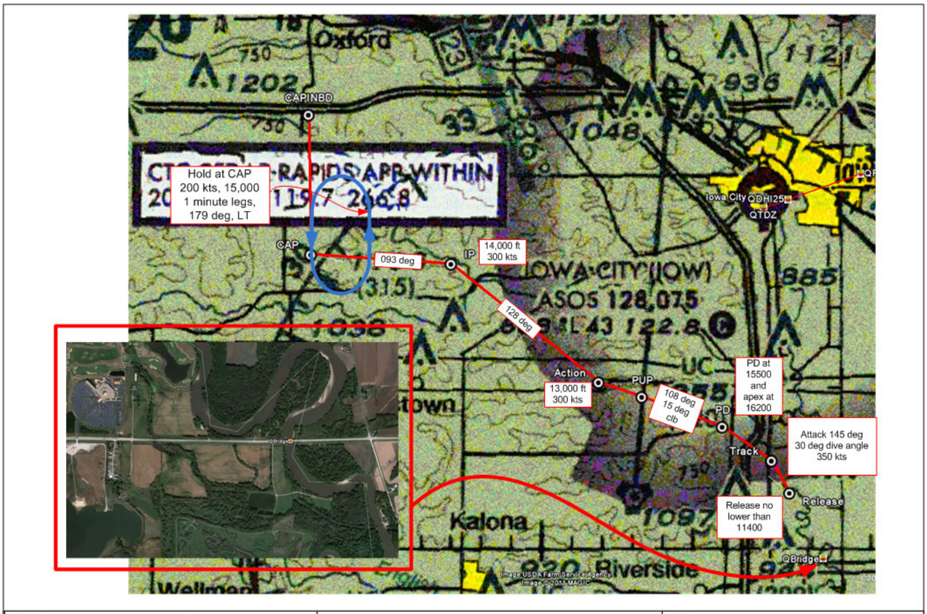
d. Rear Cockpit

Fig. 2. Instrumented Flight Simulator and Matching L-29 Flight Test Aircraft

3 Experimental Design and Procedure

The authors of this paper fully understand that simulator fidelity is a very complex concept and that our simple experiment does not color the entire gamut of fidelity. We tested three levels of fidelity as a between subjects factor. Participants in the low fidelity group flew their mission in the flight simulator using only one channel of the outside visuals. Participants in the medium fidelity group flew their mission in the simulator using all three channels of visuals. Participants in the high fidelity group flew their missions in the jet. Each group consisted of five pilots who had no military tactical flight experience.

The mission consisted of a holding pattern at a combat air patrol (CAP) point followed by a series of waypoints leading to an offset pop-up bombing pattern with a 15° climb and a 30° dive angle to deliver a Mk-82 low drag general-purpose bomb onto a target represented by the middle of the bridge deck across a river (Fig. 3). We chose this mission profile because it has a wide range of perceptual, motor, and cognitive demands ranging from a simple holding pattern, a dynamic high-speed route with precise turns and crossing altitudes, culminating in a relatively complex pop-up bomb delivery pattern that requires precise management of pitch, bank, speed, and heading in a very short amount of time.



Mission Number : 76Y Sortie Number : Pilot Call Sign :____________ Date :____________	Aircraft: F/A-18 Loadout: 6xMk 82, 500 rds 20 MM	1. IP Alpha 2. 108, 2.2 Left 3. 9.6 4. 610 5. Bridge 6. 41° 29.769'N, 91° 30.658'W 7. None 8. 750 Meters W 9. Egress West to CAP
	Target: Hwy 22 Bridge over Iowa River, East of Creekside Casino, 41° 29.769'N, 91° 30.658'W, 610	

Fig. 3. Holding Pattern, Route, and Pop-Up Attack Pattern

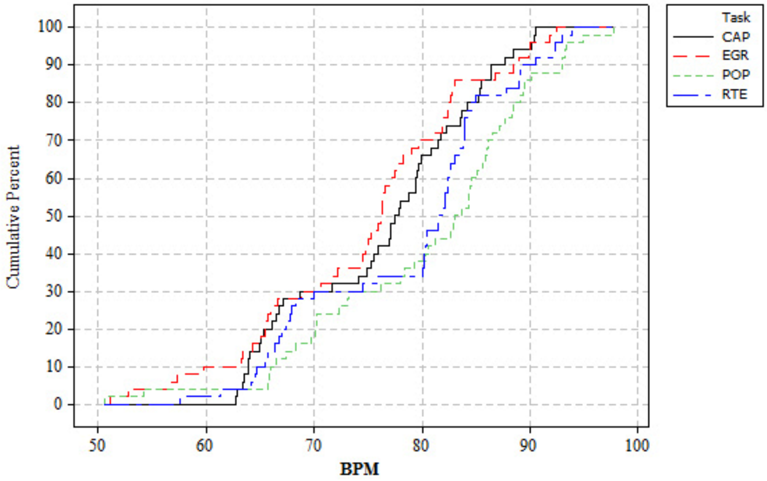
Normal pop-up weapons delivery is performed following a low-level route at 500 feet AGL. The pop-up itself actually serves to increase altitude to several thousand feet to allow for a reasonable amount of tracking time in a dive during which the bomb guidance symbology can be tracked against the desired target. In this experiment, we did not fly the route at a low level for reasons of flight safety and compliance with the required speed limit of 250 kts below 10,000 feet. Rather, we started the rout at 15,000 feet gradually descending to 13,000 feet just prior to the pop, with apex altitude of 16,200 feet, 6 seconds of tracking time and the release altitude at or above 11,400 feet. Fig. 3 shows the mission profile that was flown identically in the simulator and the real aircraft. Each pilot was given simulator training to acclimate to the flight symbology and to learn the mechanics of the route and pop. A total of 10 minutes of simulator training was provided to allow the pilot to acclimate the flight symbology. Following that, a total of 30 min. of simulator training was provided to teach the participants the basics of the route following and pop-up bombing pattern. This training was always administered with only the center channel available in the flight simulator. After training was complete, data collection was performed for score. The flight simulator groups performed their runs using either one or three channels of OSV, depending on which fidelity group they belong to. The jet group always performed their runs in the real world in the L 29 jet.

The data was analyzed with CATS that has provisions to access the tags that are placed by the experimenters throughout the runs to be able to separate the holding pattern from the route and the pop-up bombing pattern. CATS generated over 60 mission technical, neurocognitive, and physiological performance metrics. Mission technical performance was quantified in terms of the flight path accuracy (speed, offset angle, pull-up-point, climb angle, pull-down-point, apex altitude, dive angle, tracking time, release altitude, and accuracy of the weapon delivery). The physiological assessment consisted of six metrics of heart rate and short-term heart rate variability. Additionally, eye gaze metrics of performance included fixation duration, fixation count within areas of interest, lateral and vertical fixation dispersion, and distance between fixations. CATS generated over 65 neurocognitive metrics based on the average, RMS, and standard deviation of EEG power in the frontal, midline, occipital, and sensorimotor areas. Subjective workload data was collected after each pop using the Bedford workload scale and situation awareness data was collected using the SART scale.

4 Preliminary Results

Data analysis is still ongoing at the time of writing of this paper (March 1, 2011). Data for all pilots in the flight simulator has been collected at this time. Flight test data collection has been slow due to adverse winter weather, but we are making good progress with data for three subjects in the jet group already being collected. As the data analysis is continuing we are going through dozens of combinations of the dependent measures to determine which ones are statistically significantly able to predict the level of pilot workload. Preliminary results are shown in this paper for the flight simulation groups. One exciting finding is that heart rate (Fig. 4) is highly predictive of workload for the task used in this experiment.

The cumulative histograms in Fig. 4 shows that heart rate increases for increasing task demand. This is indicated by the right shift of the curves towards hire beats per minute numbers. Holding at CAP demands the least workload from the pilot. Flying the route requires considerable concentration and demands a significant amount of workload from the pilot to precisely cross the waypoints at the assigned altitudes and speeds. Flying the pop-up bombing maneuver requires very precise pull-up timing, accurate flight path angle control in the climb with simultaneous tracking of the offset heading, monitoring of the approaching pull-down altitude, proper selection of the bank angle (about 135°) at the pull-down point, a sufficient pull to achieve the correct heading change to the final attack heading and dive angle on the pitch ladder, and precise dive angle and final attack heading tracking of the CCIP bomb fall line (BFL) onto the target with a bomb release at wings level and at or above, release altitude. This entire sequence takes around 40 seconds to complete, and failure to accomplish any of the sub tasks is likely to make it impossible to achieve proper tracking and bomb release.



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Note:N=10 participants in Flight Simulator. CAP=low workload, RTE=Medium workload,
        POP=High workload, EGR=Low workload. Repeated measures Anova for Task
        F3,27=17.36, p<0.0001
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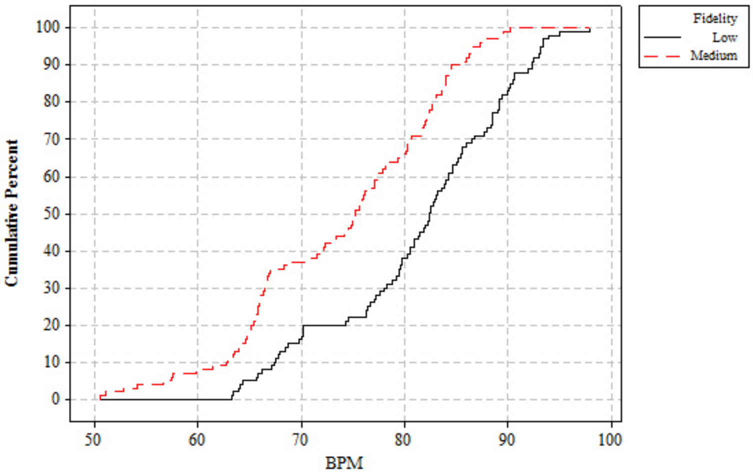
Fig. 4. Heart Rate as a Function of Mission Task Difficulty

The egress following the bomb release consists of a simple pull to a 10° flight path angle while tracking towards the egress waypoint. This demand is well characterized by the simple heart rate (beats per minute) as indicated in Fig. 4. What is rather astounding is how quickly heart rate responds to increases and reductions of workload demand as indicated by the egress (EGR), heart rate curve. The egress follows only seconds after the pop-up bombing segment has been completed, yet the heart rate responds correctly. A repeated measures analysis of variance (ANOVA) of heart rate against task indicates statistical significance with $F_{3,27}=17.36$, $p<0.0001$.

Fig. 5 shows the heart rate of the pilots as a function of the level of fidelity, with low fidelity being representative of the five pilots who flew the flight simulator with only one channel of the outside visuals and medium fidelity being representative of the five pilots who flew the simulator with all three visual channels. The higher heart rate for the lower fidelity simulation clearly indicates that the pilots had a higher workload when only one channel of outside visuals was present.

Using the very large data set that we have amassed in this study we are going to continue to use statistical, data mining, and neural network methodologies to find the best combination of physiological, neurocognitive, and flight technical performance metrics in an effort to create a robust model to predict workload. Going forward, we propose to use the existing LVC framework consisting of flight simulators (one at OPL, two at Rockwell Collins), two instrumented fighter trainer jet aircraft, and a JTAC training station to quantify neuroergonomic measures of effectiveness in pilots performing in multi-participant LVC exercises.



Note:N=10 participants in Flight Simulator. CAP=low workload, RTE=Medium workload, Low Fidelity = 1 Channel OSV, Medium Fidelity = 3 channels, Anova for Task $F_{1,198}=33.71$, $p<=0.0001$

Fig. 5. Heart Rate as a Function of Fidelity Level

5 Conclusions

The CATS neurocognitive, physiological workload measurement package described in this paper has performed very well in our flight simulator and instrumented fighter jet trainer. State-of-the-art active shielding electrodes have helped us to mitigate the effects of adverse noise and signal acquisition. In our experiment we have demonstrated that this package can be rapidly deployed on the pilot was performing I dynamics tactical maneuvering in the real fighter jet training aircraft. Perhaps the most significant conclusion of this paper is that heart rate appears to be a reliable, yet simple method to characterize pilot workload demand.

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