Real-Time Workload Monitoring: Improving Cognitive Process Models

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ABSTRACT

This article describes a study aimed at validating a method to measure workload in near-real-time in a complex human-machine-interface (HMI). Modeling cognitive processes, reviewing resource models and developing new displays and controls for aircraft cockpits require tools ensuring a sufficiently precise estimation of workload with respect to their quantitative and temporal resolution. These tools are essential not only for validating existing models and theories, but also to discover new interrelations. Currently, however, such tools are not (yet) available. Therefore, at the flight simulator center in Bückeburg (Germany) it is planned to conduct various series of experiments to test the pupillometric analysis technique "Index of Cognitive Activity" with regard to it being suitable to be used in an aircraft environment. For a validation, mental stress values obtained from different sources will be correlated with each other. A workload index with the "Index of Cognitive Activity" method will be obtained in a computer test and during a standardized simulator mission flight. A NASA TLX carried out during the flight and during mission debriefing will be used for comparison. While the first series of experiments described here aims at a general validation, further experiments will study scaling and how to validate multiple resource models.

1.0 INTRODUCTION

The aircraft crew is an essential factor for the success or failure of a military flight mission. Among other things, the crew members need to be able to perform competing tasks in a highly dynamical, threatening environment and, at the same time, always maintain a high level of attention to different system and environmental conditions [20]. The natural limitation of cognitive resources and the vast number of (often parallel) tasks are reasons why for the aircrew, critical workload levels cannot always be avoided. This phenomenon continues to be one of the major causes of flight accidents and serious incidents for manned and unmanned air vehicles [3; 11]. Every year, this costs both human lives and considerable material resources. Unsurprisingly, workload and situation awareness are object of a number of basic and applied research projects and future cockpit design approaches [1; 2; 13; 22; 24]. The common idea is to reduce overall workload levels, improve situation awareness and to define assistance systems for those situations where an overload cannot be avoided [4; 5]. This may happen e.g. through improved display and control devices or adaptive automation.

For the analysis of workload levels during various tasks and the efficiency of new HMI design concepts, many projects rely on subjective workload assessment techniques like SWAT, the Bedford Workload Rating Scale or NASA TLX [1; 7; 24]. Cognitive models and general theoretical assumptions are often based on such techniques, although their validity is still discussed. The risk imposed by models relying on these workload measurement methods is addressed e.g. in [17, 18, pp. 4-2, 10-2], reasoning that it is important to develop means of further validation.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **OCT 2010**	2. REPORT TYPE **N/A**	3. DATES COVERED -

4. TITLE AND SUBTITLE **Real-Time Workload Monitoring: Improving Cognitive Process Models**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Army Aviation Combat Development Division Achumer Strasse 1 31675 Bückeburg GERMANY**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

See also ADA564696. Human Modelling for Military Application (Applications militaires de la modelisation humaine). RTO-MP-HFM-202

14. ABSTRACT

This article describes a study aimed at validating a method to measure workload in near-real-time in a complex human-machine-interface (HMI). Modeling cognitive processes, reviewing resource models and developing new displays and controls for aircraft cockpits require tools ensuring a sufficiently precise estimation of workload with respect to their quantitative and temporal resolution. These tools are essential not only for validating existing models and theories, but also to discover new interrelations. Currently, however, such tools are not (yet) available. Therefore, at the flight simulator center in Bückeburg (Germany) it is planned to conduct various series of experiments to test the pupillometric analysis technique Index of Cognitive Activity with regard to it being suitable to be used in an aircraft environment. For a validation, mental stress values obtained from different sources will be correlated with each other. A workload index with the Index of Cognitive Activity method will be obtained in a computer test and during a standardized simulator mission flight. A NASA TLX carried out during the flight and during mission debriefing will be used for comparison. While the first series of experiments described here aims at a general validation, further experiments will study scaling and how to validate multiple resource models.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**10**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Today, non-intrusive physiological methods to assess workload have come closer to achieving applicability. These methods include EEG[1], heart rate variability analyses, blinking rate measurements, eye tracking and pupillometry. The last named method is the subject of this article, whose purpose is to briefly outline in how measuring workload in near-real-time and under near-reality conditions can benefit modeling cognitive processes and to present an experimental design planned to be conducted at the simulator center of the German Army Aviation School in Bückeburg. The study is done in a cooperation with the Leuphana University in Lüneburg (Germany), where the research project "Psychonik" analyses the role of emotions for traffic safety and methods for detecting emotions [10].

Since budgetary difficulties have delayed the procurement of the required sensor systems for this study, it is not yet possible to present any results. Nevertheless, the author wants to take the opportunity to present the experimental design and underlying conceptual considerations to help on further discussions on real-time workload monitoring.

2.0 APPLICATION OPPORTUNITIES

The degree of mental stress[2] depends on many processes occurring in the cockpit. Apart from having an impact on communication and aircraft handling, it does, for example, affect all levels[3] of situation awareness. If the mental stress is too high, the aircraft crew will run the risk of not perceiving information on the airspace environment or the technical systems. Furthermore, their abilities to judge situations and to make decisions may be limited due to the associated mental processes partly demanding a large amount of cognitive resources [23, Chapter 8 and 12]. Projection into the future (planning, mission priorities) is also likely to be affected in moments of mental stress. Integrating workload into models of human behavior continues to be a challenge.

When it comes to **cognitive modeling**, mental stress has an influence on a large number of variables, each of which is displayed in accordance with the granularity of the used or desired models. Examples of these variables include target recognition reaction times, identification, reaction to enemy fire, safe navigation and movement along the time axis (sense of time), safe control of technical systems (use of weapons), self-assuredness in taking mission-relevant decisions (continue/abort), response to parts of the crew being incapacitated, prioritization with respect to different mission targets, and many more. For examples of air traffic controller models, see [4; 12, p. 237].

Workload and it's evenly important companion Situation Awareness are affected by factors like the training state, constitution and composition of the aircrew, the operating procedures used, technical conditions such as cockpit design and equipment, the mission profile, intensity and contents, and the environmental conditions (weather, time of day) [8; 9; 22]. Determining a reliable and computable correlation between these factors and the workload will allow for using modeling to a much larger extent - either to recognize new or to validate existing correlations. Successful tools and methods for real-time workload monitoring can help with this task. As a result, simulations, whether used on the operational level or as an evaluation tool, will be able to incorporate a more detailed described chain of effect, that is both the effect the external variables have on the workload and the effect the workload has on mission-specific parameters (reaction times etc.).

Besides modeling, real-time workload monitoring would be invaluable for the **development of new displays, control devices, operational and training procedures**, both for manned and unmanned air vehicles (UAV). It not only helps to understand what happens "inside" the pilot, but also could serve as a

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[1] Electroencephalography.

[2] In this article the terms (mental) workload and mental stress are used synonymously.

[3] Endsley's three levels of SA [9, p. 5].

quality measurement tool or decision factor when comparing different pieces of equipment. When new engineering designs for cockpits and UAV ground control stations are created, human factors already has some impact [6; 14; 24]. Still, the knowledge from cognitive psychology research which actually can be implemented in system designs has to be deepened.

Several **other research topics and design concepts** might also benefit from a method to monitor workload in real-time. This includes adaptive automation, cognitive sensible pilot assistance systems (current research at the Bundeswehr University in Munich) and questions concerning task interference, based on a multiple resource theory [21; 23]. Another question of interest is how and when high workload triggers stress remediation techniques. Own observations from flight duty in simulated and real flight showed behavior patterns in high-workload-situations which are not solely explainable by a resource shortage but by behavior under stress [23, chapter 12].

3.0 METHOD

In the following, the Bückeburg simulator study is described. The general mission setup, schedule and integration in a standardization course have already been tested in a prestudy in May 2010 with alternative sensors. Unfortunately, budget restrictions have delayed the purchase of the pupillometric cameras so the study is temporarily paused.

The overall design provides for conducting two series of experiments. First, the suitability of the apparatus and software used will be validated by correlating the obtained pupillometric data with different subjectively perceived stress values. Although a benefit can already be achieved in a laboratory study, advanced workload monitoring techniques will develop more impact when being applied to more realistic environments.

If the apparatus and software have proved suitable even under the near-reality conditions prevailing in the simulator, the next step will be an analysis of the scale. A previously conducted study yielded qualitative statements [19]. Consequently, in the second series of the Bückeburg simulator study, the test conditions must be varied to allow for observing the test persons’ behavior in comparable situations under workloads of different intensity and, particularly, full-intensity workloads. It is not enough to distinguish between higher and lower workload, since most future applications require a more refined way of scaling workload. General requirements on the assessment of mental workload can be found e.g. in [23, p. 459]. If the first two experimental series have been successful, a third part should finally be able to address detailed research questions as described in application opportunities before.

3.1 Participants

The test persons of this study will be volunteers recruited from weekly CH 53 G and Bell UH-1 D (transport helicopters used in the Bundeswehr) standardization courses. They will be pilots from different regions of Germany and with different degrees of flight experience (junior, master and senior pilots). No allowances will be paid for participating in this study. The mission flight used for obtaining pupillometric and subjective workload ratings will be standardized for all participants and integrated into the relevant training schedule (4-8 participants per week).

A number of 40 test persons is desired to participate. A questionnaire will include questions on the total number of flight hours, simulator flight hours, flight hours flown in the past three months and four weeks respectively, the consumption of alcohol and nicotine and corrective lenses.

3.2 Apparatus

3.2.1 Flight Simulator

The Simulator Center in Bückeburg at the German Army Aviation School (Figure 1) offers a range of full mission[4] simulators for basic and advanced training to helicopter pilots from different nations. Currently featured are simulators of the helicopter types EC 135 (eight cockpits), CH 53 G, NH 90 and Bell UH-1 D (two cockpits each). The visual simulation, modern hydraulic systems and supporting devices like seat shaker and noise simulator generate a near-reality flight feeling. The up to 16 tons heavy simulator cockpits used for the study are moved at six degrees of freedom by 115 bar hydraulic pressure. The visual representation of the environment is done by eight projectors with a datarate of 1.54 MPixels/sec each, covering a field of vision of 240° horizontally and 90° vertically. The flight missions can be recorded and later reviewed in several debriefing rooms. The video signal from cockpit camera (showing the front of the pilots), external view, instrument panels and audio signal are recorded, together with events and the aircraft's technical parameters.

The experiment uses the CH 53 G and Bell UH-1 D cockpits, which predominantly consist of original components of the corresponding aircraft and have been installed in identically constructed domes.

Figure 1: Bückeburg's Hans E. Drebing Simulator Center (left) and a hangar with two cockpit domes (right).

3.2.2 Index of Cognitive Activity (ICA)

The ICA, a mathlab module patented by Sandra Marshall [U.S. Patent No. 6,090,051, 1999, 16], is a technique to determine a workload index based on how the pupil size changes over time. For this purpose, a fast fourier transformation is used to identify short-term changes in pupil dilation. The frequency of these changes should positively correlate with mental workload. Pupil dilations not corresponding to the desired frequency-analytical parameters will be eliminated. The aim is to obtain a workload index that is not affected by confounding factors like light or breathing.

Previous studies, for example by Maximilian Schwalm [19], proved the ICA to be generally suitable for being used in a simple driving simulator environment.

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[4] Although Bückeburg's simulators are more than just "full flight", meaning they provide movement and outside view, some will argue that they provide only limited "full mission" capabilities. For example, the aircrew, in reality consisting of three for the UH-1D and seven for the CH 53 helicopter, is reduced to the two pilots in the simulator. From the author's point of view, these restrictions are insignificant, so the term "full mission" will be used here.

3.2.3 Pupillometric Sensor System

The study requires a high-frequency measuring pupilometer with a sampling rate of 250 Hz or more. The mode of operation furthermore makes it necessary to use a helmet-mounted system, such as a modified version of Eyelink II by SR Research or comparable systems with similar technical properties having been made available on the market by now. Remote sensors lack the required visual resolution and will lose signal because of the pilot’s head movement, for example when looking out of the side window while handling external cargo.

Core element is an infrared illuminator and camera. The reflections of the pupil are then processed by an image recognition system and transferred a.o. into a pupil diameter, feeding the ICA software module. The gaze-tracking elements of the Eyelink II will be removed by the manufacturer. The remaining camera and illuminator for each eye (Figure 2, marked by a red circle) will be mounted onto a pilot helmet.

**Figure 2: Eyelink II, the red circle highlights the pupil camera and infra red illuminator.
With the permission of SR Research Ltd, Ontario, Canada.**

3.3 Conduct of the Experiment

As the combination of the sensor system and ICA has already been validated in a basic car driving simulator by BMW, this study’s first part concentrates on reproducing these results in a much more complex environment, the full mission simulator. In contrast to the previous studies, this simulator puts external effects on the test persons including acceleration force, vibration and steady and sometimes annoying sounds. The task structure is very similar to a real flight mission and much more complex than the tasks used in the driving simulator. Both factors, external effects and the wide range of tasks, will make a thorough data analysis challenging. In order to validate the use of ICA in aircraft, the first series of experiments to is made up of the following steps.

3.3.1 Questionnaire

Information about the pilots’ current mental and physical condition are recorded by a questionnaire. This includes age, gender, alcohol and nicotine consumption, visual status, sleep during the last three days and last night, sportive activities and general stress perceived. Another set of questions addresses flight experience, both in simulators and real flight: Total flight hours, mission status (student, not combat ready, limited combat ready, combat ready, maintenance pilot, instructor pilot, examiner, night vision goggles) and flight hours in the past [twelve months, three months, four weeks, seven days].

3.3.2 PC Application "Serial Recall"

First, the change of pupil size will be measured while the test person is resting and only facing a black screen (baseline), using the pupillometric sensor system and ICA method described before. Then the software Serial Recall will be used, providing the test person with exercises of varying degrees of difficulty. The test person must try to remember the characters displayed on the screen and then will have to reproduce them by using the keyboard. Different degrees of difficulty will be achieved by changing the timing (e.g. display time, memory time) and the number of characters. The aim is to check how the pilots' pupillometric workload indices correlate with the Serial Recall's difficulty settings under this very basic laboratory conditions, being later compared to the results from the simulator flight mission.

3.3.3 Simulated Training Mission

The main part of the first experimental series is the standardized simulated training mission, flown by an aircrew of two pilots sitting next to each other. The mission consists of different phases (table 1), each with their unique task structure and difficulty. Each phase is repeated to allow both pilots to be "in controls". The repetitions are designed in a way that they only marginally disrupt the flight experience. Weather and light conditions vary through the different mission phases, but are the same for each crew. Environmental conditions are manipulated by an operator in the control room, who also simulates air traffic control. In order to allow a "real flight" feeling, the tasks in the training mission are similar to those in regular training missions. The flight period used by the study is integrated in a standardization course.

Starting IFR[5] with very easy procedures, the pilots have to perform an instrumental landing at the Bückeburg airfield. The flight is continued under visual flight conditions to a training area some miles away, where some external load handling will be practiced. The final phase of flight is a transition back to IFR and two emergency procedures afterwards, one for each pilot.

Table 1: Simulator mission flight phases. Difficulty is given on a 1-10 rating after evaluation by pilots, with 10 being the highest.

Phase	Weather	Altitude	Difficulty
1 IFR Approach	Calm air, in clouds	4000 ft	2
2 VFR Flight	Low turbulence clouds scattered	500 ft, 100 ft	3
3 External Load	Medium turbulence clouds scattered	50 ft	7
4 Transition to IFR	Low turbulence clouds scattered	4000 ft	3
5 Emergency Procedure	Medium turbulence clouds scattered	0 – 4000 ft	8

(1) Mission Start: IFR Approach

The mission starts in clouds, calm air, on a long final for ILS (Instrument Landing System) approach into the military airfield Bückeburg. Long final means the pilot has sufficient time to get

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[5] Instrument Flight Rules (IFR) are procedures that allow pilots to perform their flight without visual references to the environment, only by using the instruments and air traffic control.

familiar with the aircraft and his situation as he is still several miles away from the runway. Navigational tasks or other actions to prepare the landing are not necessary. All pilots are familiar with the approach procedure which is of low difficulty. Regular startup at the airfield is not wanted since it already starts with a wide range of tasks and the challenge of hovering/air taxiing, which can be very tricky in the simulator at the beginning of a flight period. The start in clouds reduces visual stimuli and reduces the risk of simulator sickness (e.g. nausea, disorientation).

(2) VFR[6] flight

Continuing under visual flight conditions in a medium altitude, complexity and difficulty slowly increase. Navigational tasks are to be taken care of and depending on the altitude, obstacles may be a threat. Altitude changes to low level (100 ft) after reaching a certain waypoint, further increasing difficulty at least slightly.

(3) External Load Handling

The crew picks up and relocates external cargo while experiencing increased wind turbulence. This phase is expected to be challenging for most pilots, especially as aircraft operation near ground is reported as more difficult than in real flight. Physical tension may occur, especially for less experienced pilots. Attentional focus is expected to be on manual aircraft handling.

(4) Transition to IFR

After releasing the external load, the crew requests a radar pickup, where flight is continued under instrumental flight rules in a high altitude. Physical and mental stress should decrease for a few minutes. Navigational tasks are reduced to a minimum, directions coming from air traffic control.

(5) Emergency Procedures

The Aircrew’s relaxation is discontinued by an emergency condition, e.g. hydraulic failure or flame out, where an immediate landing is required.

3.4 Data Evaluation

How well does the workload index derived from the pupillometric cameras and ICA software correlate with subjective workload ratings? To answer that question, the helmet-mounted pupil camera will be active during the Serial Recall task in front of a personal computer and during the whole simulated training mission flight, as depicted in Figure 3. At three points, the mission will be paused to allow a NASA TLX for both pilots. Although more subjective ratings already obtained during the mission flight would be preferable, the number of interruptions must be kept small.

For evaluation, the five mission phases are further broken down into subphases. This is done semi-automatically by synchronizing the simulated aircraft’s properties (e.g. altitude, airspeed) with the ICA data. Afterwards a pupillometric workload index based on conflated ICA values will be computed.

For subjective workload rating scores with a NASA TLX questionnaire, the mission flight is paused three times (in phase two, after phase three and five). Additional subjective ratings will be obtained by reviewing the mission at one of the debriefing stations afterwards. It is expected that by using a playback of the mission with its various recorded signals (cockpit camera, external view, instruments, voice), the pilots can reconstruct their workload levels in the specific situations.

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[6] Visual Flight Rules are the normal procedures for flight under meteorological conditions where the pilot can see the outside of his cockpit and navigate accordingly.

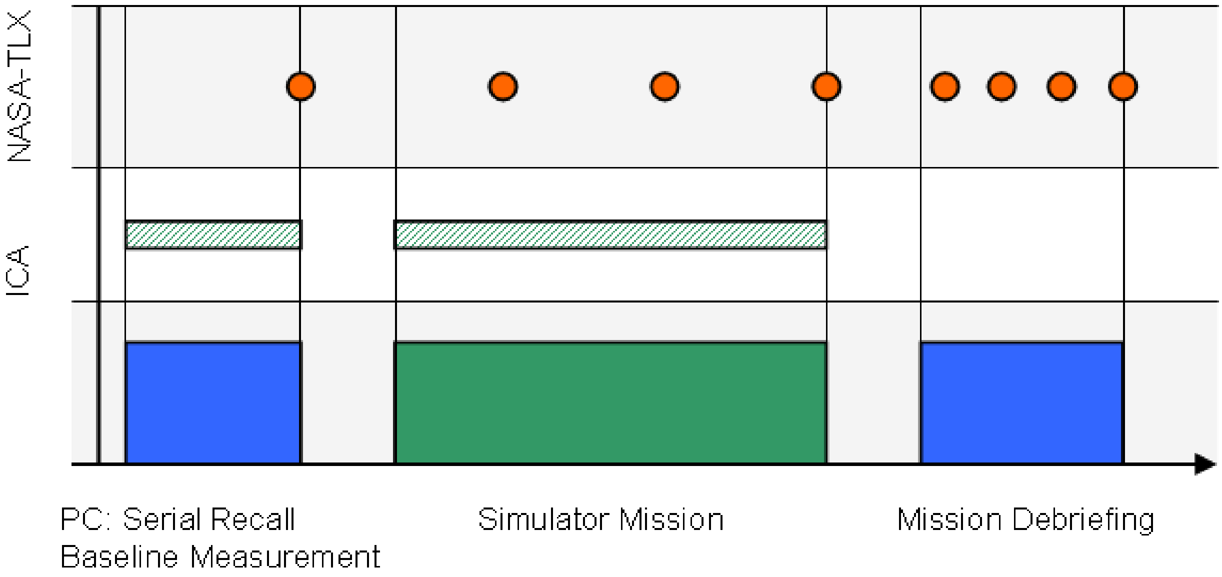

Figure 3: Times of Workload Assessment by NASA TLX and ICA Measurement.

4.0 CONCLUSION

In this article, different application opportunities for a real-time workload monitoring and an experimental design to validate a method using pupil cameras and the ICA software module have been described. Although a successful outcome of the study is highly desirable, it is of course not certain. Challenges remain: How well does the flight simulator reproduce workload levels compared to real flight? What bias will the pilots have when giving subjective workload ratings? What is the best compromise between number of data collections and acceptance by the test persons? Does simulator sickness sophisticate workload ratings?

Nevertheless, the opportunity to perform these experiments having the Bückeburg's simulators and a large number of pilot's at one's disposal is invaluable. Both are usually rare resources. Therefore, the present delay will be used a) to refine the experiment's design and b) to indentify alternate sensor systems if budget restrictions prevail.

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