2011

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Repository Citation

Wickens, D., Bagnall, T., Gosakan, M., & Walters, B. (2011). A Cognitive Model of the Control of Unmanned Aerial Vehicles. *16th International Symposium on Aviation Psychology*, 535-540.
https://corescholar.libraries.wright.edu/isap_2011/25

A COGNITIVE MODEL OF THE CONTROL OF UNMANNED AERIAL VEHICLES

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We describe a workload model of a single pilot unmanned aerial vehicle (UAV) control, which can provide the basis for extension to multiple UAV control and supervision. The model predicts multi-task capabilities based upon the multiple-resource model of human time sharing. Elements of the model are described related to task demand, resource conflict, and resource allocation (task priority). We then demonstrate its applicability to predicting pilot performance in the MQ-1 Predator, describing the "workload spikes" during a typical mission, and demonstrating ways in which high workload can be mitigated.

The control of multiple unmanned aerial vehicles (MUAVs) presents tremendous challenges first and foremost for the pilot, who must fly more than one aircraft at a time, in a manner that imposes extremely high workload. The extent to which such workload is excessive can be answered, in part, from pilot-in-the-loop simulations (Dixon, Wickens, & Chang, 2005; Wickens, Levinthal, & Rice, 2010). But also relevant are computational models (Cummings & Mitchell, 2007; Goodrich, 2010). However, the viability of such computational models of MUAV depends on valid models of the operator of a single UAV. We describe one such model below. In our description, we attempt to be both general, so that guidance can be provided for applications to other environments, as well as specific to the particular modeling project. This paper discusses the workload model that was used to study the MQ-1 Predator system and the findings of the study. The MQ-1 Predator UAV was designed to be controlled by two dedicated operators: a pilot and a sensor operator. Under this configuration, the pilot is responsible for aviation, navigation, strike, communication, and systems monitoring while the sensor operator is responsible for intelligence, surveillance, and reconnaissance (ISR), which includes target tracking, lasing (arming and firing of lasers for ordnance guidance and target illumination), systems monitoring, and communication. In addition to the complex tasks that need to be performed, what makes the work further challenging is that each of these operators has over five displays (e.g., a heads-up display (HUD), chat display, and a tracker) to obtain information necessary for the successful control and operation of the UAV. The work undertaken during the MQ-1 effort focused on developing a thorough workload model that predicted operators' overall workload associated with performing the mission tasks when looking at these displays.

Multiple Resource Model (MRM)

The fundamental model architecture that we harnessed was the multiple resource model of multi-task performance (Wickens, 2002, 2005, 2008), which is designed to predict the amount of interference imposed by two or more tasks performed concurrently. That is, it is a model specifically designed to address multi-task and task "overload" situations, very characteristic of the flight deck, UAV control station, or other high tempo task environments (including driving). The model architecture contains three fundamental elements:

A *task demand (scalar)* component that describes the workload, or demand for mental resources, of each task to be performed in the multi-task ensemble. As we will see, this total demand can be distributed across resources within each task, creating a vector. But at the simplest level, the interference between two component tasks is related to the sum of demands of the two, where each task demand is the sum across that task's resources.

A resource-specific *conflict component*, which penalizes a task-pair to the degree that they compete for common resources. As a simplifying example, two visual tasks will generally compete more than a visual and auditory task. Thus, the task demand and the resource conflict can combine, in a way described below, to predict the total task interference or dual task decrement.

A *resource-allocation component* that essentially allocates the decrement between the two tasks, in inverse proportion to task importance. Hence, a pilot will typically allow maintaining stability of the flight dynamics (aviate) to dominate addressing chat communications if the two are imposed at once. Multi-task researchers often speak of a primary and a secondary task. By definition, when these compete, the secondary task is that which is assumed to bear the most interference. Adhering to optimum resource allocation is related to good cockpit task management (Chou, Madhavan, & Funk, 1996; Funk, 1991).

Importantly, different aspects of this model have been validated in both driving (Horrey & Wickens, 2003) and to a lesser extent in aviation (Wickens et al., 2003; Sarno, 1995)

Application of the Model to UAVs

Our current application begins with parallel identification of demand and resource conflict components. This was accomplished by first referring to doctrine manuals to identify major meta-tasks in a UAV mission, such as handing-off, flying to target, surveillance of target, etc. (Eaton et al., 2006; Nagy, Muse, & Eaton, 2006). This was followed by extensive interaction with subject matter experts (SMEs), working with the crew station description to identify the workload associated with each meta-task and to break the meta-task down into subtasks such that each subtask could be associated uniquely with its own goal and workload characteristics. Because we were interested in the highest workload meta-tasks of the mission, we focused initially on the five subtasks that appeared to define most of the activity within the mission: aviating, navigating, chat communications (digitally with a display and keyboard), oral communications, and systems monitoring. We then used the workload values, assigned by the SME for each meta-task, to define the proportional workload of the tasks contained within, but these proportions were based on the resource-interface analysis described as follows.

Resource-interface analysis. As noted above, each task can be associated with demands on each of five resources within the current version of the multiple resource model: visual, auditory, cognitive, speech, and motor.[1] Any task must be associated with demands in one or more of these resources. Furthermore, each of these resources may be linked to one or more **interfaces** in the cockpit workstation. For example, a HUD is clearly associated with the visual channel, as is the chat room text display.

We also obtained data from the SMEs on the relative percentage of use that they assigned to each interface during the meta-task in question. Using reverse engineering, we were then able to associate the total demand of each task with a demand for each resource for the tasks, where proportion of time used was translated into a demand for the resource using the interface in question.

Computing task interference. Having completed this task description vector for all tasks performed concurrently during a meta-task, we examined each task pair that might be time-shared and computed its predicted interference by summing the total demand value for each task and summing the task interference across resources for the two tasks. For the two tasks shown in Table 1, these values, in red, are shown across the top (task A) and down the columns on the left (task B). Computing the resource conflict between the two tasks in question is described below.

Table 1. *Conflict Matrix*

		Task A				
		Visual	**Auditory**	**Cognitive**	**Speech**	**Motor**
	Task B	**1**	**0**	**1**	**0**	**2**
Visual	**2**	**0.8 or 1.0**	0.7	**0.6**	0.4	**0.6**
Auditory	**0**		0.9	0.6	0.8	0.4
Cognitive	**0**			0.8	0.5	0.5
Speech	**0**				1.0	0.8
Motor	**1**					**0.6 or 0.8 or 1.0**

Below and to the right of the red task A and B demand vectors, Table 1 represents a conflict matrix, the heart of any multiple resource approach. The numbers within each cell depict how much a resource used in the task across the columns (A) will compete with a task down the row (B). These values range from 0 (no conflict whatsoever) to 1.0 (maximum conflict). The specific assignment of values shown in the table is based on the multi-dimensions structure of multiple resource theory, and the reader is referred to Wickens (2002, 2005) for details. But, to cite two intuitive examples, the value of 0.4 between motor and auditory indicates that it is relatively easy to

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[1] Other versions include tactile, spatial versus verbal cognition.

listen while manipulating with the hands (low conflict), whereas the high value (0.8) between auditory and speech indicates the great difficulty of listening while talking.

The table also highlights two additional complexities. Within visual/visual conflicts, the two values indicate the greater conflict (1.0) when two visual sources are separated (e.g., the view outside and on a head-down instrument panel) than when they are close (0.8) (e.g., view outside and a HUD). The latter is still high but not impossible. Within motor-motor, the lower value (0.6) results when two hands are used (e.g., joystick while keyboarding with the other hand) and the mid value results when a single hand is used in an integrated control (joystick manipulation with finger controls mounted as in a HOTAS). The highest value (1.0) is when a single hand must be used for controls in two different locations.

Using the conflict matrix in the above table, it is possible to assign the task vector of two concurrently performed tasks to the rows and columns. Task A represents the chat task, and Task B represents the task of aviating. From this representation, then, it is possible to compute the conflict score by summing the cell demands of all cells that are occupied by a non-zero entry in the column above and the row to the left (modulated as needed by the qualifiers for visual-visual and motor-motor interference). These cells are bold faced in the table. As is evident, this sum could range from 0.4 to 10.6 (all cells occupied).

Total predicted interference (sometimes referred to as predicted workload) is then computed by summing the weighted total demand and resource conflict component. This weighting is required because of the different maximum possible values of the two components: 10.6 for resource conflict and 30 for the sum of the maximum resource demand vectors across the two tasks. Regarding the latter, if, within each resource, the maximum is 3 (e.g., workload per resource could be 0, 1, 2, 3), then the maximum total demand is 30 (sum of maximum Task A demands is 3+3+3+3+3=15 and similarly the maximum demand vector sum for Task B is 15, for a total of 30) . Thus, to weight each component equally, the resource conflict score should be multiplied by 30/10.6 = 2.83.

The third component of the multiple resource conflict architecture is, of course, the task priority score. As the model adds the task demand and conflict to predict a total decrement, this decrement can be allocated proportionally to the row or column task in a manner inversely related to some judgment of task importance made either by the operator or imposed by a mission planner. Clearly, if the overall interference score is low, allocation will have little influence, as both tasks will be performed quite near their ceiling value in any case.

Regarding resource allocation, in the current application, we always designated one task (within each meta-task) as primary. All other tasks were secondary, and the model only computed interference between the primary task and one secondary task at a time. The proportion of task-pair interference assigned to the total interference score was based on the relative amount of time that each secondary task was being performed.

Task shedding and the "red line." It became evident as we coded the tasks that there were times when a mission planner designated that certain sets of tasks should be performed concurrently, but they simply could not be, either because of their high demand values or because of conflict values =1.0 in occupied cells. Intuition also tells us that there are times when we must cease performance of one task altogether rather than perform it in a degraded manner, when demands become excessive. In the parlance of workload researchers, these are the circumstances in which workload has "exceeded the red line" and tasks are shed (Wickens, 2008). Such task shedding has two direct implications. First, it means that the workload predicted by summing tasks requested to be performed during a given period (we called this **prescriptive** workload) may be far less than that experienced by the operator, as s/he has shed tasks, in a closed loop fashion, to keep workload manageable. We called this **descriptive** workload. Second, it means that a comprehensive workload model must predict which task will be shed and how long it may remain unattended (or "unserviced" in the language of cueing theory) before it is resumed.

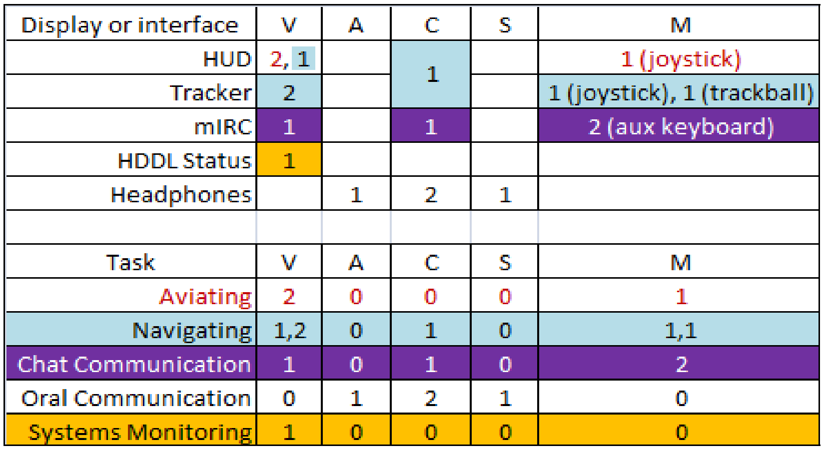
Human Performance Model (HPM)

For this effort, a human performance simulation model was developed to capture an entire mission of an MQ-1, from the pilot and sensor operator gaining control of the aircraft ("gaining handover") back to relinquishing control of the aircraft ("losing handover"), with stages of en route to target, reconnaissance, strike, and en route (return to base) in between these two endpoints.

The Improved Performance Research Integration Tool (IMPRINT) was the software used to develop the human performance model. IMPRINT is a simulation and modeling tool that estimates manpower, personnel, and training (MPT) requirements and identifies constraints for new weapon systems early in the acquisition process. It is government-owned software and consists of a set of automated aids to assist analysts in conducting human performance analyses (Allender et al., 1995). Based on modeler's inputs, IMPRINT computes a time line of the workload experienced by an operator over a mission so that relative comparisons can be made within and between missions. It is important to note that for this effort, IMPRINT's built-in graphical user interface was not used to enter the workload values for each meta-task. Instead, code was written within each meta-task in the model to record workload.

Before the IMPRINT model was developed, the high-level functions and meta-tasks performed during the mission were identified using the results of our task analysis. Each meta-task was then decomposed into primary and secondary tasks. Next, we mapped the five mental resources that were needed to interact with each of the displays and/or interfaces to perform each task based on the meta-task description. Finally, the associated task demand values for each resource-interface pair were generated. An example of a meta-task within the Strike function was "The pilot discovers a target and obtains orders for a strike." This meta-task consisted of the following tasks: aviating, navigating, chat communication, oral communication, and system monitoring. The primary task was navigating, and the remaining tasks were considered secondary tasks.

Table 2. *Task Demand and Resource Allocation*



Display or interface	V	A	C	S	M
HUD	2, 1		1		1 (joystick)
Tracker	2				1 (joystick), 1 (trackball)
mIRC	1		1		2 (aux keyboard)
HDDL Status	1				
Headphones		1	2	1	
Task	V	A	C	S	M
Aviating	2	0	0	0	1
Navigating	1,2	0	1	0	1,1
Chat Communication	1	0	1	0	2
Oral Communication	0	1	2	1	0
Systems Monitoring	1	0	0	0	0

Table 2 shows the resource-interface and task demand assignments of this meta-task. The different tasks are color coded. Within each cell is the demand imposed by the task /resource combination in question. Total demand for each task (sum of resource demands) was based upon SME inputs, coupled with general workload ratings assigned in the documents provided (Eaton et al., 2006; Nagy, Muse, & Eaton2006). For each task, the analyst, working with the task description and SME consultant decided how to allocate the total task demands to the separate resource channels. As a simple example, the task of systems monitoring (yellow) had its entire (low) demand associated with the visual channel.

After all of the meta-tasks were identified, this information was used to develop the human performance model in IMPRINT. Workload analysis was conducted for 18 pilot meta-tasks (composed of 71 tasks) and 16 sensor operator meta-tasks (composed of 55 tasks; see Bagnall et al., 2010 for details).

Selected Results

Figure 1 shows a comparison between the prescriptive and descriptive workload for the pilot throughout the simulation run. The prescriptive workload for the pilot is the workload associated if all prescribed tasks for each meta-task were performed simultaneously. (Note that the scale of the y axis for the two graphs is different. This was done to see the "spike" in workload in the descriptive workload graph.). For the pilot, the highest workload occurred within the strike portion while performing the "Pilot maneuvers aircraft into proper position for strike" meta-task. This meta-task requires a substantial amount of cognitive and visual resources as well as fine motor control. The two displays that the pilot monitors during this meta-task are the HUD and the Tracker. The pilot's attention is divided between these two displays almost equally while performing the aviating and navigation tasks. It is also important to note that during the majority of this task (approximately 90% of the time) the pilot is either talking to, or listening to, oral communications over the headset. One suggestion to lower the pilot's workload during this meta-task is to limit the amount of conversations being monitored once the decision has been made to launch the weapon.

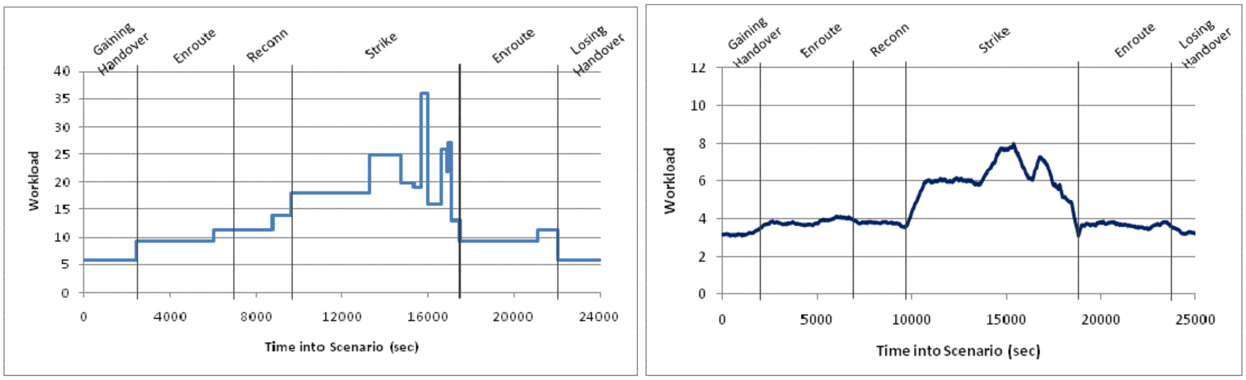


Figure 1. Prescriptive Workload (left) Versus Descriptive/Moving Average Workload (right) for the Pilot.

While the above discussion and findings apply only to one pilot meta-task ("Pilot maneuvers aircraft into proper position for strike"), it is to be noted that the HPM model has been set up such that an analyst can run different mission configurations (for example, nonstrike scenarios such as an emergency situation) and identify points (meta-tasks) of high workload for that particular mission profile and detect what tasks-mental resources-display combinations are contributing to those high levels. The analyst can then play what-if scenarios by either re-allocating or shedding some of these tasks to be addressed by automation and subsequently investigating the impact of that on operator workload. Similarly, the effects of experience on overall workload can be studied by either reducing or increasing (if a person with lesser experience is performing) the mental demands placed on a task.

In addition to the pilot workload, because the sensor operator is an integral part of the traditional configuration, the sensor operator's workload was also studied. For the sensor operator, the highest workload occurred while performing "SO guides the missile." This meta-task requires a substantial amount of cognitive and visual resources as well as fine motor control (i.e., the sensor operator uses a joystick to control the direction of the missile). During this task, the sensor operator is monitoring the location of the missile relative to the target on the HUD and controlling the missile's direction using the joystick. The sensor operator does not participate in any conversations (oral or chat) during this task. Therefore, this should serve as an indication to mission planners that adding any additional tasks such as a communication task would only further increase the workload levels experienced by the sensor operator for this meta-task.

As noted in the Introduction, with some additional assumptions regarding task switching and supervision, the core of this model can be embodied in a workload model of multiple UAV control, and an attempt at this has been made under the same effort. However, several assumptions were made for the MUAV configuration, and the results were not discussed in this paper. Further, it is important to note that the current application has not yet been validated against performance data in an actual Predator simulation.

Acknowledgments

The research reported in this document was performed in connection with contract MSIAC 09-0016/0035 for the Modeling and Simulation Information Analysis Center. The views and conclusions contained in this document are those of the authors and should not be interpreted as presenting the official policies or position, either expressed or implied, of the U.S. Government unless so designated by other authorized documents. Citation of manufacturer's or trade names does not constitute an official endorsement or approval of the use thereof. The U.S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation hereon. The authors would like to acknowledge LtCol Roscoe Van Camp at Creech Air Force Base for his contributions to this effort.

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