Aviation Human Factors Division
Institute of Aviation

University of Illinois
at Urbana-Champaign
1 Airport Road
Savoy, Illinois 61874

Using Interference Models to Predict Performance in a Multiple-Task UAV Environment – 2 UAVs

Christopher D. Wickens, Stephen Dixon, and Dervon Chang

Technical Report
AHFD-03-9/MAAD-03-1

April 2003

Prepared for

Micro Analysis and Design
Boulder CO

Contract ARMY MAD 6021.000-01

Report Documentation Page		*Form Approved* *OMB No. 0704-0188*

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **APR 2003**	2. REPORT TYPE	3. DATES COVERED **00-00-2003 to 00-00-2003**
4. TITLE AND SUBTITLE **Using Interference Models to Predict Performance in a Multiple-Task UAV Environment - 2 UAVs**		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) **University of Illinois at Urbana-Champaign,Aviation Human Factors Division,Savoy,IL,61874**		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

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Twenty four pilots flew simulated missions in an unmanned air vehicle (UAV) simulator under both single and dual UAV control, and in three conditions: a baseline condition, a condition in which certain information was displayed auditorally, to offload the heavy visual demands of the mission, and a condition in which flight path tracking was automated. Three tasks were performed within each UAV workstation: (1) Meeting the mission goals, by flying to 10 command target waypoints and reporting intelligence information at each of these command targets, (2) monitoring a 3D image display for targets of opportunity on the ground below the flight path,(3) monitoring the health of on-board system parameters. Upon reaching a command target, or seeing a target of opportunity, pilots were required to enter a loiter pattern, zoom in and inspect the image. Pilots could also retrieve command target coordinates and report information at any time they wished. The data were evaluated in the context of three models of concurrent task performance, strict single channel theory, single resource theory and multiple resource theory. The results indicated a cost to dual UAV control in all three tasks, although this cost varied in its magnitude. The results also indicated that both the auditory and the automation assistance improved performance, and reduced the dual task decrement, relative to the baseline condition. In particular, the auditory display of system parameter failures enabled a large degree of parallel processing. Various analyses were carried out to examine the extent to which models based on each of the three attention theories were adequate in predicting the data. Some aspects of the data were consistent with each model. Thus a valid model to account for all aspects of the task would need to incorporate mechanisms based on each model. A separate section of the results applies the Army?s IMPRINT model to predicting the workload imposed by the various conditions.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**64**	

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

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1.0 Introduction

Since the first use of airplanes in war over Tripoli, Libya in 1911 (Milnet, 2001), hundreds of thousands of pilots have been killed or sustained career-ending injuries. Most of these accidents occur during combat situations, but many can also be ascribed to training accidents and peacetime flying. The Air Force, Navy and Army all support air combat units and spend millions of dollars each year training and preparing pilots to take on a multitude of combat roles (e.g., fighters, bombers, helicopters, transports, etc.). When one of their pilots is killed or injured, the financial loss to the military is significant, not to mention the emotional loss to their units and families. It has always been a priority of the military to find ways to protect their pilots and keep them from danger while still fulfilling the mission requirements.

Within the past few decades, the US military has made a concerted effort to produce Unmanned Aerial Vehicles (UAVs) to fulfill many mission requirements without exposing a human pilot to combat danger. A UAV can be flown by a specially trained pilot from a remote location hundreds or thousands of miles from the actual combat situation. These aircraft are cheaper to produce than normal warplanes, and when one of them gets shot down, the financial loss is significantly smaller. These aircraft can also carry out missions that would expose human pilots to extreme combat or environmental dangers that were previously impossible to justify.

The Army operates a small fleet of UAVs, including Hunters and Shadows. These UAVs are used primarily for reconnaissance, and can fly at 60 knots or loiter at 12,000 feet for approximately 18 hours. A four-man team operates these vehicles: 1) a mission commander, who may be at a remote location from the operators at a forward base; 2) an external pilot responsible for taking off and landing the aircraft; 3) the AVO (aviator operator); and 4) the MPO (mission payload operator).

The AVO is primarily responsible for flying the UAV, monitoring the craft parameters for abnormalities, attempting to correct any vehicle problems that occur during the mission, and following flight-path guidance from the MPO who is processing real time images. The MPO is responsible for finding targets, manipulating the camera to pan and zoom on those targets, directing the AVO to adjust flight paths to better view those targets, and detailing those targets to mission command. These responsibilities are extremely demanding both cognitively and physically.

In the future, the Army intends to merge the responsibilities of the AVO and the MPO under a single operator. This single operator will also be expected to control multiple UAVs or unmanned ground vehicles from the same workstation—we will use the term Remotely Piloted Vehicle (RPV) to denote the control of any generic vehicle, whether it be air or ground. The challenge of controlling multiple RPVs dramatically increases the mental workload for pilots.

The purpose of this experiment is to evaluate the capabilities of a single pilot to meet the multiple task demands of flying single and multiple RPVs, and to evaluate the adequacy in which different models of multiple task performance account for the data. In this review of the literature, we will analyze the mental workload demands that these responsibilities put on the RPV pilot. We will first discuss the general multiple RPV challenge to human cognition and workload modeling. Then we will analyze the interference between visually presented tasks,

visual monitoring, and cognitive processing. Next we will study efforts to model task interference via multiple resources and single channel queuing, followed by a detailed discussion of previous research done by others in this area. Lastly, we will focus on the current study and present the proposed experimental simulation.

2.0 The General Multiple RPV Challenge to Human Cognition and Workload Modeling

Once the responsibilities of the AVO and the MPO have been merged, a single operator will be required to fly the UAV, monitor the craft parameters for abnormalities, correct any vehicle problems that occur, manipulate the camera, find targets in the camera monitor, adjust flight paths to review a target area, and report back details to mission command. These responsibilities impose a vast amount of mental workload upon the pilot.

Mental workload can be described as the relationship between resource supply and task demand. If supply exceeds demand, then performance is constant. But if demand exceeds supply, then performance will decrease as the resource demand (workload) further increases. Each of the pilot's responsibilities impose a certain amount of demand. The question is how much supply the pilot has available to cope with that demand, and when the demand reaches a point where performance drops due to a lack of resources.

2.1 Flying the UAV

Flying a UAV is more than just a simple tracking task. While automation does provide a good deal of support for flight control and stabilization, it does not always work properly (Parasuraman et al., 2000) and it does not handle all flying requirements. In the following, we discuss generic mission requirements as they might be imposed on the single pilot of a generic UAV, flying without high levels of automation support. The pilot is responsible for keeping the plane on course and choosing new flight paths when necessary. If changes are imposed on the flight plan, then the pilot must manually input the new coordinates and make sure the aircraft proceeds as directed to the new location. If a target is selected for review, the pilot must put the aircraft into a loiter pattern around the target.

While flying the UAV, the pilot is using all four stages of the human information processing system (sensory input, perception/cognition, selection of action, execution of action), involving both cognitive and physical requirements. Pilots must understand the data they are receiving, memorize and be able to recall those data, make decisions based on those data, and when course changes are required, respond by physically using the hands to manipulate the aircraft.

2.2 Monitoring and correcting the craft parameters

While flying the aircraft, the pilot must also keep track of the craft system parameters which are portrayed on screen. If any of these parameters becomes abnormal, the pilot must decide if corrections need to be made, and then make those corrections when necessary.

Sometimes the pilot will be able to ignore the flying task while concentrating on the system monitoring task, but occasionally the situation may force the pilot to attempt to perform both tasks at once. This obviously creates some visual conflict, given that the sources of

information are separated, as well as cognitive conflict, since both tasks can simultaneously require all four processing stages, as when flying requires adjustment of a course trajectory and system monitoring triggers a corrective intervention.

2.3 Target search, manipulating the camera, and reporting to mission command

The pilot is also responsible for manipulating the camera and looking for targets. In the simulation examined in the present experiment, the camera pans down over the earth at a 90-150 degree angle in a continuous live feed. If something of interest is seen, the pilot might need to swivel or zoom the camera for better inspection. This task can again require all four stages of the human information processing systems, along with potentially high demands on spatial working memory, especially when a potential target has been found.

Detecting a target requires substantially different processes from manipulating the camera. With the aircraft flying at 60 knots over a variety of terrain, it is often difficult to pick out exactly what is on the ground below, particularly if the pilot is also trying to simultaneously adjust the flight pattern or correct abnormal craft parameters on other displays. Visual scanning difficulties can be compounded by wide visual angles of the areas to be scanned, clutter, and nonsalient targets, all features common to the UAV mission. During vigilance tasks such as the one described in this experiment, pilots must detect intermittent, unpredictable, and infrequent targets, while guarding against vigilance decrements, which commonly occur even within the first half hour of the watch (Funk, 1991; Wickens & Hollands, 2000). In addition to detecting the target, the pilot must also determine what the target is, if it is of any importance, and whether or not to report it to mission command.

We can easily imagine situations that involve two or more competing task conditions depending on what else is occurring. For example, upon detecting a target of interest, the pilot might have to readjust the flight plan to loiter around that target. At the same time, the pilot might notice an abnormality in the craft parameters, forcing a correction, and in that scenario, might need to handle all three of these tasks simultaneously. By adding a second UAV to the scenario, these task conflicts can grow exponentially.

Finally, the pilot must make reports (verbal responses) to mission command based on what is seen. If all of these task requirements are imposed at once, the mental workload on the pilot might be too much to allow parallel processing, forcing the pilot to revert to some degree of serial processing. In this case, the pilot must decide which task to do first, which next, and so forth; that is, to implement a task management strategy (Wickens & Hollands, 2000). One objective of the research is to provide data which will support a model of how the pilot addresses these workload overload situations.

Clearly, one of the most important aspects of flying involves the interference between visually presented tasks, visual monitoring, and cognitive processing. This is a crucial issue when determining how much mental workload the pilot is experiencing and how well she or he can be expected to perform. The next section will focus on these issues of interference and highlight some of the important aspects that must be included in any workload model.

3.0 Interference Between Visually Presented Tasks, Visual Monitoring, and Cognitive Processing

Flying a UAV can be described as a supervisory control task that frequently involves multiple-display monitoring. This can be further complicated by secondary tasks with higher level cognitive and motor components. Interference between visual monitoring and other visual tasks—whether these involve pure monitoring, or visual input plus higher level cognitive/motor tasks—is a crucial aspect of workload modeling and must be incorporated into any successful model. Furthermore, it is often more effective to offload some of the visual tasks to the auditory channel or to incorporate automation into one or more of the tasks in order to reduce visual workload, and total workload, respectively. This section will focus on visual-visual, visual-cognitive/motor, visual-auditory, and automation research in order to provide data that will predict multi-task efficiency under different circumstances.

3.1 Supervisory monitoring

Visual information acquisition generally falls into one of two categories: visual search, as in target search described within the image display in section 2.3, and supervisory control/sampling, as in system monitoring described in section 2.2 (Wickens et al., 2003) and in the UAV operator's decision to deploy attention across the different areas of interest. Extensive research has been done on visual search (e.g., Brogan et al., 1993; Wolfe, 1994), but we are equally interested in supervisory monitoring, which can be distinguished from visual search by four key features (Wickens et al., 2003): 1) The operator is supervising a continuously evolving series of dynamic processes instead of looking for a static target, 2) The operator is more concerned with noticing events rather than finding particular targets, 3) Measuring the proportion of visual attention allocated to different regions of the visual field, and the tasks supported by that attention, is more important than target detection RT, and 4) The operator is as much concerned with *when to look* as with *where to look*.

In a model of supervisory sampling, which integrates concepts from earlier models by Senders (1964), Carbonnell et al. (1968), and Moray (1986), Wickens et al. (2003) proposed four mediating factors that drive the allocation of visual attention: 1) Salience, 2) Effort, 3) Expectancy, and 4) Value. This SEEV model encapsulates findings from previous research and models described below.

Salience is based on the physical features of an object that make it noticeable. Examples of salient events might include: bright lights, loud noises, highlighted information, or auditory alerting (Wickens & Hollands, 2000). Making potential events within the environment salient so that the operator can easily find pertinent information is an example of bottom-up (stimulus-driven) attentional control, as opposed to top-down (goal-directed) control, which relies on the operator's deliberate state of attentional readiness (Egeth & Yantis, 1997). Onsets are one example of stimulus-driven attentional controls that make objects more salient, as they instantly attract attention, particularly in the periphery of the visual system (Jonides, 1981; Remington, Johnston, & Yantis, 1992; Yantis & Hillstrom, 1994).

Effort is required to move attention from one area to another. Experiments have shown that greater distances between visual sources produce greater deficits in performance (Martin-

Emerson & Wickens, 1992). Sanders (1970) described three general regions into which visual stimuli can fall during a monitoring task: 1) within foveal vision (0 – 2 degrees); 2) requiring eye movement (2 – 30 degrees); and 3) requiring head movement (30+ degrees). Two tasks whose information sources both lie within the foveal region might produce very little switching cost, while two tasks that appear further apart may produce more switching (Wickens, 1992; Wickens et al., 2002). Martin-Emerson and Wickens (1992) analyzed visual angle separations and found a significant increase in event response time and tracking error for separations between a tracking display and a visual RT display greater than 6.4 degrees, with no performance decrements in either response time or tracking for visual angles below 6.4 degrees. Schons and Wickens (1993) also found performance decrements with spatial separations between tracking and event monitoring displays beyond 7.5 degrees, with larger decrements in cluttered displays. Andre and Cashion (1993) found a linear increase in tracking error for increasing visual angle, with a large drop-off in performance in the head field (>56 degrees).

Expectancy (bandwidth) was employed as a tool for modeling monitoring behavior by Senders (1964), and describes one part of the top-down, goal-directed movement of attention. Proponents of Senders' model asserted that bandwidth was the main determinant of monitoring behavior; that is, an operator would visually scan displays with high bandwidth more often than those with low bandwidths. Senders' model, using eye movements in a supervisory task, indicates that the allocation of attention is proportional to bandwidth or event expectancy.

The impact of expected value, or the importance of an information channel multiplied by the operator's expectancy that something will occur in that channel, was first added to Senders model by Carbonell (1966), who turned to more realistic tasks in order to emphasize the importance and impact of actions taken by the operator. Carbonell, Ward, and Senders (1968) found that this model predicted pilots' scanning behavior well in a flight simulator with experience pilots. A subsequent model of expected value, developed by Moray, Neil, and Brophy (1983) and Moray, Richards, and Low (1980), which used realistic experiments involving fighter aircraft, predicted with reasonable accuracy what proportion of time was spent fixating on the aircraft and other display features. Sheridan and Rouse (1971) also followed up Carbonell's work by incorporating expected value into their model of supervisory sampling. They found that humans underperformed when compared to the model predictions of optimal information sampling.

As mentioned, the SEEV model incorporates all of these influences into a descriptive model, and then uses a prescriptive model of expectancy and value to successfully predict human attention allocation. As with the Carbonnell and Sheridan models, expected value is considered the primary predictor of visual sampling, with the value of the *task* replacing the value of the visual *event*. Wickens et al. (2003) had experienced pilots fly in a high fidelity flight simulator, while engaging in traffic detection. In the first two experiments, the pilots used a cockpit traffic display, and in the fourth experiment they used different forms of data link displays (e.g., textual instructions). All three experiments showed a strong fit between model predictions and actual percentage of viewing time.

Besides the four elements described in the SEEV model, there are other important factors to take into consideration when predicting performance in a supervisory monitoring task. For example, expertise will produce a more calibrated agreement between the operator's expectancy

and importance (the mental model) and the true bandwidth and value of events. Moray (1986) notes that data from studies involving skilled pilots (e.g., Carbonnell, Ward, & Senders, 1968) show more optimal monitoring prescriptions than less skilled participants (e.g., Sheridan & Rouse, 1971), suggesting that training benefits performance in supervisory monitoring. Wickens et al. (2003) also suggested that well-trained pilots allocate attention more optimally than their novice counterparts.

An operator's useful field of view (UFOV) can also have effects on monitoring performance. UFOV is defined as "an index of the total visual field area from which target characteristics can be acquired when eye and head movements are precluded". In other words, UFOV is the visual area that a pilot can examine without moving his/her eyes or head, while still procuring useful information from that visual stimulus. A pilot's UFOV may vary depending on the density of visual stimuli present in the visual field (Wickens, 1990), and varies from 1-4 degrees of visual angle (Mackworth, 1976).

3.2 Visual + Cognitive

UAV pilots often face a unique challenge when visual tasks do not simply involve monitoring. They sometimes must fly (tracking task) the aircraft while simultaneously analyzing possible targets, and/or diagnosing and responding to system failures (cognitive task). UAV pilots, in particular, may be called upon to analyze a potential target or system failure on one monitor, or in one channel, while not losing sight of their aviating requirements on the other. Adding a cognitive secondary task can lead to impairment of attention-switching abilities, otherwise known as "cognitive capture" (Gish & Staplin, 1995; Tufano, 1997), or even to total "cognitive lockup" (Moray & Rotenberg, 1986), which impedes the operator from returning attention to the initial primary task. Primary task performance can suffer immensely while a pilot focuses most, or all, of her attention on dealing with the secondary task. When designing a system that requires a cognitively challenging secondary task, it is important to determine exactly how that secondary task will affect performance in other concurrent tasks.

Although there are a wealth of studies which show interference between cognitively challenging primary and secondary tasks (e.g., Lee, 1997; Moray, Richards, & Low, 1980; Moray, Neil, & Brophy, 1983; Moray & Rotenberg, 1986, 1989; Strayer & Johnston, 2001; Tsang & Rothschild, 1985), we only discuss four specific experiments because they model workload scenarios that are common to the UAV pilot. We believe the results from these experiments can be generalized to multiple-task scenarios that UAV pilots face.

Sarno and Wickens (1995) had pilots concurrently perform a tracking task, a monitoring task, and a decision task. The first-order pursuit tracking task resembled flying an airplane, while the monitoring task required the pilots to determine when two instrument pointers went into a red danger zone—subjects pushed a directional button to the left or right, depending on which way the pointer went. The results of this experiment showed that more difficult decision tasks caused more interference with the primary tracking task than simple decision tasks, with greater disruption due to increased verbal task difficulty than with increased spatial task difficulty.

Liu and Wickens (1992) required pilots to perform a tracking task while simultaneously executing either a spatial decision task (i.e., predict the future position of a vector) or a verbal

decision task (i.e., mental arithmetic). By manipulating the scanning distance (long / short), type of scanning (certain versus uncertain target locations), and decision codes (spatial / verbal), they were able to show that the inherently spatial visual scanning task produced more interference with a concurrent spatial task than with a concurrent verbal task; that is, tracking error, decision accuracy, and workload all suffered more when both tasks involved spatial activities.

Wickens, Sandry, and Vidulich (1983), in Experiment 1, had pilots time share a primary tracking task (either first-order velocity dynamics or second-order acceleration dynamics) with a secondary memory search RT task responded to manually or verbally. The memory task required participants to respond as quickly as possible to a set of displayed letters that may or may not have been part of a designated memory set of characters. The results of reaction time and error rates suggested that manual responses disrupted tracking more than verbal responses, while visual inputs disrupted the memory search task more than auditory inputs; that is, increased perceptual competition disrupts a cognitive task more than a motor task. Furthermore, when the workload of the tracking task was increased by changing the dynamics from first-order to second-order, the advantages of the separate modalities were augmented; that is, higher tracking orders (i.e., acceleration dynamics) cause more interference with cognitively challenging tasks than with simple perceptual tasks.

None of these three studies explicitly used an RPV-type cognitive task, yet the collective message derived from their results was that difficult and spatial tasks which compete for the same cognitive resources show greater disruption with concurrent tasks than easy or verbal tasks that use different resource modalities. One study which did examine an RPV-type task that was both spatial and difficult (but not in a dual-task context), was conducted by Gugerty and Brooks (2001). One of the more difficult cognitive tasks that UAV pilots must perform is assessing directional axes of buildings, or other structures, while maintaining their concurrent tracking duties. Gugerty and Brooks asked UAV pilots to determine which directional side of a particular building the parking lot with vehicles was located. They were presented with a top-down map which showed their current tracking direction, and a 3D egocentric map which showed the building and parking lots. Using the top-down map, which was always north-up, the pilots had to diagnose which way they were flying and then transfer this information to the 3D map in order to determine camera heading. A first experiment presented static maps, while a second experiment required the pilots to fly from one point to other in a dynamically changing environment, and then complete the direction task. Although Gugerty and Brooks did not examine visual-cognitive interference, they did note the extra difficulty of the cognitive task by pointing out that UAV pilots produced accuracy of less than 50% in certain camera headings (e.g., 120 or 240 degrees). Since we used this task in our own simulation, it is important to see how challenging this secondary task can be, even when performed in isolation.

The general message offered in these studies is that concurrent cognitive side tasks cause more disruption of the primary tracking task than simple monitoring tasks do, particularly when the cognitive task is difficult, is visually displayed, involves spatial judgments, or is more demanding. The UAV environment described at the outset forces pilots to undergo all of these conditions at certain points during their missions, so it is critical to find ways to predict performance in situations beyond a simple visual monitoring task.

Fortunately, there are ways to relieve the added burden of a cognitive side task. One way is to introduce automation, which can be used to replace human cognition by that of the automation and thereby relieve task interference, particularly in visual-cognitive tasks. In the UAV simulation, pilots may be responsible for manually aviating and navigating their aircraft. Finding coordinates and making spatial judgments on flight paths consume valuable cognitive resources. By automating components of the tracking task, the cognitive aspects of flying are eliminated, reducing a visual-cognitive task to visual-visual monitoring. By removing the cognitive burden of the tracking task, performance in the secondary task should improve since visual monitoring takes up fewer overall resources than visual-cognitive tasks. The current study will examine the benefits of this automation by automating the tracking task in one of the conditions in order to analyze the effect of reducing a monitoring + cognitive task to a monitoring + monitoring task.

3.3 Visual + Auditory

Many studies have shown greater interference between two tasks that are done simultaneously and require processing by the same, rather than different, modality (Wickens & Liu, 1988). Because of this, there is interest by designers of complex systems such as UAVs in finding ways to offload some of the visual tasks to the auditory channel in order to reduce task interference. Wickens (1980) asserts, "…in a heavy visual environment, auditory displays will improve time-sharing performance." In his review, Wickens cited 18 studies on dual-task performance and concluded that 13 of those studies showed performance in cross-modal configurations to be superior to intramodel configurations, particularly when the visual fields were widely separated in the latter. Wickens' findings imply that the beneficial source of the Visual-Visual (VV) → Auditory-Visual (AV) shift is at least peripheral in nature.

Many driving studies take these conclusions a step further by suggesting that the benefit is not only peripheral, but also that different processing modalities use different cognitive resources, and that offloading some of the visual tasks to the auditory channel would reduce task interference even in non-peripheral tasks (e.g., Labiale, 1990; Liu, 2001; Parkes & Coleman, 1990; Streeter, Vitello, & Wonsiexicz, 1985). For example, Gish, Staplin, Stewart, and Perel (1999) had participants perform a primary driving task while dealing with a secondary cognitive task of reading or listening to a set of instructions, and found that driving performance, (i.e., the percentage of correct braking responses to traffic events), and the secondary task performance (i.e., the percentage of correct responses to the navigational task) were both better under the auditory condition than under the visual condition.

It is important to note that offloading visual tasks to the auditory channel does not always produce better performance on *both* tasks. A number of investigations involving a continuous tracking task combined with a discrete reaction time task have shown that, on average, offloading to the auditory channel improves performance on the discrete task whose modality is changed, while either showing no benefit to, or even *reducing,* performance in the visual tracking task (Israel, 1980; Lee, 1997; Pamperin & Wickens, 1987; Tsang & Wickens, 1988; Wickens, Braune, & Stokes, 1987; Wickens, Dixon, & Seppelt, 2002; Wickens & Goettl, 1984; Wickens, Vidulich, & Sandry-Garza, 1984). This phenomenon may be attributed to a kind of auditory preemption, wherein the auditory channel "grabs" the operator's attention away from the primary task to focus on the secondary auditory task.

Furthermore, offloading to the auditory channel may sometimes decrease performance in both the tracking task *and* the secondary task (e.g., Matthews, Sparkes, & Bygrave, 1996; Stanton & Baber, 1997; Tsang & Rothschild, 1985). Helleberg and Wickens (2001) presented air traffic control (ATC) instructions to participants either visually or aurally and found that the primary task (traffic monitoring and flight path tracking) suffered as well as the secondary task (accuracy of communications task) from auditory delivery of ATC information.

As Wickens and Liu (1988) pointed out, it is sometimes difficult to predict exactly when offloading to the auditory channel will improve performance. Wickens, Dixon, and Seppelt (2002) point out that visual angles and preemption can moderate the auditory benefit during a VV to AV shift. The greatest benefit to auditory offloading comes when the visual-visual conditions require widely separated displays, so that auditory offloading eliminates visual scanning. On the other hand, auditory delivery may help the secondary task, while disrupting the primary task, because of an auditory preemption effect of the secondary task.

In summary, UAV pilots are often faced with supervisory control situations that involve monitoring multiple workstations or displays, resulting in problems of dual-tasking. These problems can be further exacerbated by cognitively challenging secondary tasks which may result in cognitive capture or lockup. Automation may eliminate some of the cognitive demands, thereby reducing overall task load, and restore higher levels of dual-task performance. Changing information delivery to an auditory channel may accomplish the same goal by redistribution of task load across separate resources, particularly in the UAV environment where visual channels are widely separated. The findings above have generated different theories regarding why this dual-task interference happens (e.g., Craik, 1948; Kahneman, 1973; Moray, 1986; Navon & Miller, 1987; Pashler, 1994; Temprado et al., 2001; Wickens, 1980). In the next section, we will discuss different workload models, postulating different psychological mechanisms, that have been generated from three of these theories. If validated by the empirical data reviewed above, and to be reported in the experiment described below, these workload models can be used to predict performance in future dual-task situations.

4.0 Three Workload Models

Having a quantitative workload model is extremely useful to system design, as it allows system engineers to compute the capability of humans to operate machines before any time or money is spent on developing those machines (Laughery & Corker, 1997; Pew & Mavor, 1998; Wickens, Vincow, Schopper, & Lincoln, 1997). Workload models can usually be categorized in one of the following two ways: models derived from the Single Channel Theory which consider tasks too difficult to allow time-sharing, and models derived from Single or Multiple Resource Theory which assume that some conditions will allow parallel processing or concurrent processing (Sarno & Wickens, 1991).

The resource models are based on the concept that an operator has a limited capacity of resources and that different tasks require varying amount of resources (Kahneman, 1973; Moray 1969). When the task demand *exceeds* this finite capacity, it results in some task interference, to the degree that is related to the difficulty (resource demand) of the task (single resource theory) and/or to the competition for overlapping or shared resources (multiple resource theory). For a workload model to be successful, it must first be a good task interference model; that is, predict

when the performance in one task will suffer as more resources are demanded for another task, or as structural changes are made to one of both tasks.

4.1 Single Channel Theory (SCT)

The origins of single channel theory (SCT) can be traced back to the early postulations of the "single channel bottleneck" in the human information processing system. Proponents of this theory claim that two high speed tasks can not be performed concurrently, but will result in total abandonment of all (or part) of one task until the other task is completed (Broadbent, 1958; Craik, 1948; Welford, 1967). SCT assumes that no parallel processing or timesharing can take place and that all tasks are performed in a series. Time is a limited resource (Hendy, Liao, & Milgram, 1997) and can not be shared across tasks. Some experiments have presented two visual tasks (Neisser, 1969) as well as two auditory tasks (Cherry, 1953; Glucksberg & Cowen, 1970; Moray, 1959; Norman, 1969; Mowbray, 1964) and appear to provide results that agree with the SCT model, in that successful performance in one task entirely precluded success in a concurrent task.

The existence of the psychological refractory period, or PRP (Telford, 1931; Kantowitz, 1974, Meyer & Kieras, 1997; Pashler, 1994), also appears to support SCT assumptions. The PRP describes a situation in which two RT tasks are presented close together in time (Wickens & Hollands, 2000, p. 367). PRP experiments (see Pashler, 1994, for a review of the literature) indicate that the processing of information for one task mandates a delay in processing the stimulus for a second task that arrives just after the first task, with that delay increasing as the two tasks are presented closer in time. Pashler (1994) points out, however, that while the original bottleneck theories assumed a perceptual bottleneck, his later studies show this bottleneck to actually be in the response selection stage.

Much of the evidence for single channel theory comes from the basic laboratory research of the PRP paradigm. However, other work has provided evidence for single channel behavior in more complex task environments. As an example, Hendy et al. (1997) analyzed task interference in an air traffic control environment. Using a low-fidelity simulated radar screen, participants controlled the altitude and direction of aircraft moving across their field of vision. The goal was to route the "aircraft" successfully to their destinations in the least amount of time. By manipulating the number of aircraft and the length of the update interval (how often new information appeared on the screen), the researchers attempted to show that humans can only perform one task at a time. They found that for the dependent variables *error*, *success*, and *correct*, a time-based model more consistently predicted the results than did an intensity-based (resource) model. However, the authors clarify their conclusions by stating that they are not returning to a strictly single-channel model of traditional timeline analysis, but rather that concurrent processing is assumed when different processing structures come into play.

Moray and Rotenberg (1986) cited "cognitive lockup" as one reason for single channel processing. In their study, participants were responsible for monitoring four simulated thermal hydraulic systems, similar to Crossman and Cooke's (1974) bathwater task. After a period of time, one of the systems would fail (i.e., a blockage in an outflow pipe), resulting in a decrease of flow through the valve. In the following trial, a second system would fail 75 seconds after the first system failed. The data showed that the time participants took to detect the second failure

was much longer than the time to detect the first failure, suggesting that cognitive lockup while dealing with the first failure had prevented the operator from effectively monitoring the rest of the systems and noticing the second failure. Moray and Rotenberg reasoned that people tend to deal with problems serially, rather than switching between tasks.

Kerstholt et al. (1996) extended this paradigm by introducing an additional behavioral response that would allow participants to stabilize a faulty subsystem temporarily while they dealt with another fault. If the operator ignored this optimal strategy, in favor of resolving the first problem completely before moving onto the second problem, it would stand to reason that humans prefer strict serial processing over more rapid switching even when it leads to suboptimal behavior. Their supervisory control task involved visually tracking four subsystems, diagnosing problems when they occurred, and correcting those failures before the system went into automatic shutdown. Their general results agreed with their "cognitive lockup" hypothesis; that is, most participants failed to use the temporary stabilization option. However, individual subject data varied greatly, and some participants showed optimal behavior not consistent with cognitive lockup.

Since SCT offers a baseline performance measure, it is an excellent theory with which to compare to other theories. However, while the studies highlighted above appear to validate SCT, weaknesses in the theory show up in experiments not specifically designed to evoke single channel behaviors (e.g., Meyer & Kieras, 1997), as well as basic laboratory research explicitly designed to disprove SCT (e.g., Schumacher et al. 2001). Sarno and Wickens (1995), mentioned previously, compared their data to models predicted by SCT, and found no correlation between predicted and obtained decrements. They rejected the time-based model in favor of resource models which were more sensitive to the resource demands of the tasks involved and better predicted differences in the obtained dual-task performance data.

In summary, SCT has different manifestations. All versions of strict SCT predict that progress on information processing can only take place on one task at a time, and therefore the completion time for two tasks imposed concurrently will equal the sum of the completion times for each done alone. This concurrent completion time will increase to the extent that information for a second arriving task is closer in time to the initiation of the first arriving task. These two predictions will be examined in the current research.

Within this class of strict SCT versions, predictions may vary as a function of how frequently attention (and therefore processing) is switched between the two tasks. If the switch is only performed once, such that the first arriving task is fully completed prior to beginning processing of the second task, then the form of "cognitive tunneling" or "lockup" described above, is observed. However, more rapid switching will allow both tasks to absorb the single channel delay, even as the sum of their completion times adheres to the strict SCT predictions.

Other less strict versions of SCT assume that there is parallel processing at earlier stages (Pashler, 1994). However, a major focus here will be on situations in which early processing will be likely to be single channel because it is based on widely spaced visual inputs which cannot support concurrent processing (Moray, 1986).

4.2 Single Resource Theory (SRT)

Single resource theory (SRT) differs from SCT in that task interference prediction is a function of cognitive resources rather than the amount of time available. Resource theory allows for concurrent tasks, or parallel processing, while strict SCT does not. Moray (1967) developed the concept of a "limited capacity central processor" which gives humans the ability to share resources between tasks in certain situations. This concept evolved into a model of attention by Kahneman (1973) and applied work by Rolfe (1973). Their models equated the attentional resources with "mental effort" and enabled concurrent processing of the tasks. While generally predicting less effective concurrent task performance with greater task difficulty, the models allowed motivation, and a subsequent mobilization of more effort, to partially overcome the penalties of increased task difficulty (Vidulich & Wickens, 1985).

Resources, whether physical or mental, can be strategically allocated to different tasks when needed (Wickens, 2002). If one task is very simple and requires almost no resources (e.g., tapping ones fingers on the table), then it is "data limited" (Norman & Bobrow, 1975), and ample resources can be allocated to another concurrent task. For example, a pilot might take 20 seconds to adjust the throttle. This same pilot might also take 10 seconds to bank an airplane. Under the assumptions of strict single channel theory, these two tasks cannot be done in less time than the sum of the two tasks; that is, it will take 30 seconds to perform both tasks. But under the assumptions of resource theory, the easier task (adjusting the throttle) should consume fewer resources than the more difficult task (banking the airplane). Adjusting the throttle is an almost automated task, and these types of tasks may demand very few resources (Fitts & Posner, 1967; Schneider, 1985). In this scenario, while simultaneous execution may produce some degraded performance of one or both tasks, the operator should be able to do both tasks in less than 30 seconds—the amount of time required as predicted by single channel theory—and will probably complete them both in 20 seconds, the amount of time of the longest task. That is, the time required to do two tasks concurrently is less than the sum of the two single task times, and interference will result from their concurrence, not the postponement of one task or the other.

4.3 Multiple Resource Theory (MRT)

The multiple resource theory (MRT) proposed by Kantowitz and Knight (1976), Navon and Gopher (1979), and Wickens (1980) expands upon single resource theory by making the assumption that variance in dual task performance is not simply attributed to the difficulty (quantitative resource demand) of the components, to the levels of automaticity, or to the resource allocation strategy between them (i.e., choosing to emphasize one task more than another) (Wickens, 2002), but also to the differences in time sharing efficiency that support the concept of separate resource structures (Kantowitz & Knight, 1976; Wickens, 1980). As mentioned previously regarding visual-auditory presentations, two tasks which utilize different resource structures are performed more efficiently than two tasks which use the same resource structures (Kantowitz & Knight, 1976; North, 1977; Wickens, 1980), and can sometimes result in almost perfect time-sharing (Allport et al., 1972; Schumacher et al., 2001). For example, driving while listening to the news on the radio is much easier than driving while reading the same information in print. Driving and reading both use visual resources, while driving and listening to the radio use separate visual and auditory resources. Performing two visual tasks

(VV) simultaneously often results in poorer performance than performing an auditory and visual task (AV) (see section 3.3 for studies which support this view).

The 4-dimensional multiple resource model proposed by Wickens has four categorical and dichotomous dimensions (Wickens & Hollands, 2000):

1. Processing stages – resources used for perceptual and cognitive activities differ from those used for selection and execution of responses (e.g., Israel, Chesney, Wickens, & Donchin, 1980; Israel, Wickens, Chesney, & Donchin, 1980; Shallice, McLeod, & Lewis, 1985). For example, when driving a vehicle, the operator can execute maneuvers while simultaneously perceiving other vehicles around her.

2. Perceptual modalities – as we have noted above, it is sometimes easier to divide attention between the eye and ear than between two visual or two auditory channels (e.g., Parkes & Coleman, 1990; Rollins & Hendricks, 1980; Seagull, Wickens, & Loeb, 2001; Wickens, Sandry, & Vidulich, 1983). For example, is easier for pilots to listen to instructions while scanning the outside world than to read information off a display while performing the same scanning task.

3. Visual channels – focal and ambient vision appear to be associated with different resource structures (Leibowitz, Post, Brandt, & Dichgans, 1982; Previc, 1998; Weinstein & Wickens, 1992). For example, it is quite common for people to foveate on a target while processing other peripheral visual stimuli when walking, driving, flying, etc.

4. Processing codes – there appears to be a distinction between analog/spatial processes and categorical/symbolic processes (Polson & Friedman, 1988) particularly between manual and vocal responses (Martin, 1989; McLeod, 1977; Tsang & Wickens, 1988; Vidulich, 1988; Wickens, 1980; Wickens & Liu, 1988; Wickens, Sandry, & Vidulich, 1983; Sarno & Wickens, 1995). For example, one can draw a map while simultaneously explaining directions.

Both SRT and MRT are extremely useful when predicting performance in different dual-task conditions. Their particular strengths lie in predicting the changes in dual-task interference that might be brought about by making changes in task difficulty (SRT) and in the interface (MRT), while SCT is limited to task interference predictions based only on the amount of time the different tasks consume.

There are clearly some circumstances in which SCT adequately accounts for data, particularly in some RT tasks (see Schumacher et al., 2001, for an exception), conditions with a dedicated need for foveal vision and widely separated visual displays, possible overload of 3- or 4-task combinations (Liao & Moray, 1993), and possibly the circumstances that trigger "cognitive tunneling" as discussed in Section 3.2 above. We hypothesize that one of the circumstances that may be more likely to be modeled by SCT is the multiple workstation environment typical of the UAV scenario discussed at the outset. In order to examine this hypothesis, we will now review the small set of studies that have examined time-sharing across

multiple workstations, with particular emphasis on those which might have tried to model the dual (or multiple) task performance breakdowns.

5.0 Multiple Workstations

Although there is a wealth of data on multi-channel monitoring, some of which has been described above, there appear to be very few studies in the literature that have addressed the monitoring of multiple systems, and in particular, multiple replicas of identical systems (such as the 2 UAV problem described at the outset). Furthermore, fewer still have examined the workload implications of increasing the number of such systems.

As one example, Murray and Caldwell (1996) manipulated the number of displays to be monitored and found significant performance penalties in multiple-platform controls; that is, even a moderate number of displays produced response time penalties, evident at relatively low levels of complexity. However, Murray & Caldwell did not use their results to test workload theories (e.g., no single channel model tests), which prevents full relevance from being observed. Furthermore, the tasks associated with each display were relatively simple compared to those involved in UAV control.

A search of the literature failed to locate any additional studies that examined operator supervisory control of multiple replicas of the same system. However, two studies will be considered in some detail that examined supervisory control of multiple complex tasks, displayed in visually separated locations. In one approach approximating the complexity of a multiple-UAV workstations, Liao and Moray (1993), created an experimental paradigm consisting of four tasks: 1) manual compensatory tracking task, 2) "radar-like" monitoring task, 3) choice reaction time (CRTT) task, and 4) mental arithmetic task. They also created a quantitative model that they feel is partially validated and predicts performance adequately enough to be practical and useful in most system design scenarios. Their calculations were all programmed into MicroSAINT, a software modeling simulator. If SCT were correct, then multiple-task experimental performance measures would equal those predicted by the model simulation. Furthermore, a successful validation of SCT would help to constrain the domain of applicability of other competing theories.

During the first experiment, which was used to create the model, these four tasks were performed individually (single-task condition) and then all four were carried out simultaneously (4-task condition). During this experiment, the model was adjusted to fit the data. During the second experiment (validation of the model) the tasks were done in pairwise conditions. The model, having been adjusted for fit during the first experiment, was measured directly against the data from the second experiment in order to validate the model.

Their findings reveal that the simulation model did rather well in predicting some single task conditions. In the 4-task condition, the simulation model once again predicted most of the performance measures. Overall, this appears to be a good fit, but it is important to add that the subjects were forced to remove their hands from the joystick when making responses. This naturally forces single-channel processing, because it is impossible to continue tracking without holding the joystick. Furthermore, as mentioned previously, the simulation model in this first

experiment was adjusted to better measure actual experimental performance, bringing into question the integrity of the "fit" between the model and the experimental results.

To properly validate the model, the authors conducted two more experiments, whose results were compared directly to the finished model without further adjustment. Unlike the first experiment which involved a four-task scenario, these validation experiments involved dual-task scenarios. The authors report that the model did a fair job in predicting overall performance. However, it overpredicts tracking error in the first validation experiment, as well as overpredicting CRTT in the second validation experiment. As the authors point out, actual performance of the tracking task and CRTT task was *better* than the model predictions, indicating that some parallel processing had occurred.

As noted, the two validation experiments in the Liao and Moray study only involved dual-task conditions. As seen in the Sarno and Wickens (1995) study mentioned previously, MRT typically does a better job of predicting dual-task performance than SCT does, particularly when displays are close enough together to facilitate parallel processing (e.g., eliminate the single channel bottleneck created by the need to access foveal vision), or when certain tasks are offloaded to other non-visual channels. Even though Liao and Moray made no attempt to offload some of the visual tasks to the auditory channel, their data still indicate some parallel processing, which would be predicted under the resource models. Offloading to other channels might have resulted in even more parallel processing.

Since it appears to predict performance well in some multiple-task conditions, clearly the single channel model is the baseline model against which we can compare more sophisticated resource models to understand how much added variance they can account for in dual task performance.

The second study we review in depth employed the same paradigm used in the current research. Wickens and Dixon (2002) looked at many of these workload issues surrounding auditory offloading and automation in a high-fidelity UAV environment and compared their results to all three interference models. They had pilots fly a UAV through a series of mission legs designed to replicate a typical Army reconnaissance mission. During the mission, the pilots were responsible for flying from one command target to the next (using a 2-D top down map), while simultaneously searching for, and analyzing, targets of opportunity (TOO) in a 3-D egocentric camera display, and monitoring system parameters for possible failures. They were also required to remember flight instructions presented in a message box at the beginning of each leg, and could refresh their memory at any time by retrieving the information.

One condition, using all manual control and visual displays, measured baseline performance in tracking error, system failure (SF) detections and response times, TOO detections and response times, and recall of the flight instructions. Another condition provided auditory alarms which alerted the pilots to SFs represented by slowly oscillating vertical bars that occasionally went "out of bounds", as well as auditory flight instructions, offered through synthetic voice. A third condition offered automated flight control, which relieved the pilot of having to manually fly the aircraft.

The authors reported that auditory alarms were beneficial in improving detection rates as well as reducing response times to SFs that occurred concurrently with tasks which were in the easy to medium difficulty range (e.g., orienting UAV, normal flight, searching for TOOs), but not with those that occurred concurrently with highly challenging tasks (e.g., target inspection). Cognitive lockup was cited as a possible cause for this apparent lack of parallel processing; that is, despite the pilots ears having access to the auditory tone that alerted them to a SF, they appeared not to divert their attention to address the failure, while engaged in the most heavily demanding tasks. However, it was unclear whether the lockup was strategic (pilots' choice) or structural. Analysis of the memory task revealed improved performance in the auditory condition due to increased parallel processing; that is, offloading one of the visual tasks to the auditory channel allowed pilots to perform both tasks concurrently rather than switch back and forth, as was necessary when all tasks were displayed visually.

In contrast to the auditory offload, automated flight control not only improved tracking, but it also improved detection of the TOOs, as well as detection of the SFs which occurred during the early stages of a mission (i.e., orienting UAV, normal flight). An added bonus was reducing the number of repeats for the flight instructions, as pilots no longer had to remember fly-to coordinates for the next waypoint.

Differences in performance between simple dual task combinations (e.g., flight control and SF monitoring) and difficult dual task combinations (e.g., target inspection and SF monitoring) can be explained by resource models due to changes in task difficult. On the other hand, if the difference between easy and hard tasks is characterized by time differences, then these results can also be predicted by SCT. The finding of improved performance via auditory offloading can only be predicted by multiple resource models, as the other two models discussed do not make such predictions. The apparent cognitive lockup found when SFs were combined with target inspection appeared to be predicted by the single channel model.

6.0 The Current Study

The current experiment was designed to examine the UAV paradigm used by Wickens and Dixon (2002), in both single (replicating Wickens & Dixon) and dual UAV control conditions. In addition to doubling workload in the dual UAV condition, the second primary difference between this, and the previous study, was the addition of motivational incentives for good performance, to determine if such incentives, by inducing a greater mobilization of effort, could mitigate the negative effects of cognitive tunneling observed in the previous study.

To review the paradigm used in the previous study, pilots performed three primary tasks: (1) meeting the mission goals of "fly to and report", (2) monitoring for TOOs and reporting them, and (3) monitoring for system failures and correcting them. It is noted that each of these three tasks, in turn can be subdivided into 2 or 3 phases. (1) Mission goals: (i) read and initiate trajectory, (ii) monitor flight path, (iii) loiter, zoom and describe command target. (2) TOO task : (i) monitor 3D image display, (ii) loiter, zoom and describe TOO. (It will be noted that the loiter phase of tasks 1 and 2 is identical in its demands). (3) SF task: (i) monitor SF display, (ii) identify SF, type in identity and current coordinates. A subtask of Mission goals, involved exercising the opportunity to retrieve the CT instructions if necessary. Pilots also performed the three tasks under each of three conditions: a) baseline, b) auditory offload in which CT

instructions and SF's were presented auditorally, and c) automation offload, in which flight path tracking was automated after the CT coordinates were entered.

Table 1 presents the four tasks, and three conditions, along with a third dimension which describes the estimated task demands of each, along the three stages of information processing, perception, cognition and response. Each stage is associated with an experimenter-assigned demand value, assigned on the basis of the least integer ordinal heuristic, by which ordinal relations between demand values are preserve, but the smallest integer (or half integer) values possible are chosen (Wickens, Helleberg, Horrey, Goh, & Talleur, in press). This produces a range in values between 0 and 2. On this basis, it is possible to identify conflict points of concurrent task requirements between the three major tasks and their subtasks, when the mission time line of possible task overlap is presented. This time line is shown in Table 2, which describes the sequence of possible activities within each leg. Where there is no task component active, the cell in the table remains blank. Where there is an active task component, the demand values shown are based on the average demand value, across all three stages within the baseline condition as shown in Table 1 (Corresponding tables can be constructed for the AUD and ATM offload conditions). As such, a total interference score, based upon single resource theory, can be computed simply by summing the demand values of all active tasks at a given moment. For example, during the "initiation" phase of each leg, a prediction of interference level would be 2.0 (1.7 + 0.3), an identical value to that observed during forward flight, (1.0+0.7+0.3), which requires an added task (TOO monitoring) but reduced demands on the mission task because the flight trajectory does not need to be selected, only monitored. It will be noted that the SF task row actually contains two demand levels, one, for SF monitoring, which is always active, unless a SF occurs, and the other, for SF-reporting, that is only active on those phases when a SF occurs and is detected.

Table 1. Demand values in perceptual, cognitive, and response stages for the different tasks and conditions.

| | MISSION TASK | | | | | | | | | TOO TASK | | | | | |
| | Initiate | | | Fly | | | Inspect | | | Monitor | | | Zoom | | |
	P	C	R	P	C	R	P	C	R	P	C	R	P	C	R
BL	2	1	1	1	1	1	2	2	2	2	0	0	2	2	2
AUD	1	1	1	1	1	1	2	2	2	2	0	0	2	2	2
ATM	2	1	1	½*	0	0	2	2	2	2	0	0	2	2	2

| | CT INSTRUCTION RETRIEVAL | | | SYSTEM FAILURE TASK | | | | | |
| | | | | Monitor | | | Respond | | |
	P	C	R	P	C	R	P	C	R
BL	1	1	0	1	0	0	2	1	1
AUD	½#	1	0	½+	0	0	2	1	1
ATM	1	½@	0	1	0	0	2	1	1

* Flying demands for ATM are reduced because all that is necessary is to monitor position along the flight path, not deviations from it.

Auditory perception of CT instructions are reduced because pilot can listen to them while concurrently focusing attention on the nav display to find the required coordinates.

@ Cognitive demands of CT instruction retrieval are reduced in the automation condition, because pilot only needs to retain information about the report requirements, not the CT location.

+ Perceptual demands of monitoring are reduced because of automatic auditory onset capture.

Table 2. Active concurrent tasks. Estimated demand values are shown. The values for SF monitoring and SF report are offset, to indicate that these cannot occur concurrently. The "?" for CT information retrieval reflects the uncertain pilot-dependent aspect of this task.

| | PHASE OF MISSION LEG | | | | |
| | Initiate | Fly | TOO Inspect/Report | Fly | CT Inspect/ Report |
TASK					
Mission	1.7	1.0	--	1.0	2.0
TOO	--	0.7	2.0	0.7	--
SF-Mon	0.3	0.3	0.3	0.3	0.3
SF Report	1.3	1.3	1.3	1.3	1.3
Retrieve CT?	--	0.7	--	0.7	0.7

On the basis of the data presented in Tables 1 and 2, it is possible to make a number of predictions regarding the effects of the different conditions. Based upon a pure SRT model, we predict that the level of performance decrement will be directly related to the number of "active tasks" as defined by the cell entries in Table 2, and how these entries may be deleted by auditory and automation offloads.. However additional tests of single channel theory can be made on the basis of more detailed time line analysis that considers the delay in processing concurrently performed tasks, and how this delay is influenced by arrival time differences..

Based upon single resource theory, performance decrement levels can be predicted by summing the demand values within each column of Table 2 defining a task phase, as described above.

The predictions from multiple resource theory are somewhat more complex, as these require integrating the active task combination matrix in Table 2, with the stage-defined resource demands of Table 1, and incorporating additional consideration of the differences between auditory and visual resources, and between verbal and spatial resources, not described in Table 1. These features are represented in modeling based upon the IMPRINT software, described later in this report. However, the most important predictions of MRT are related to the changes in task interference brought about by auditory offloading of SF monitoring, and CT information. Both of these changes are predicted by MRT to reduce the interference with all other visually displayed tasks during the times when the SF monitoring task is active, and during those pilot-chosen instances in which the CT information is retrieved.

Finally, we note that the above task representations and their predictions apply to single UAV flying. We predict that they should apply to dual UAV flying as well. Furthermore, two additional model-based predictions can be made in transitioning from the single to the dual UAV conditions. First, predictions from strict single channel theory would dictate that, since twice as much time is occupied in dual UAV flight, all of the decrements should be doubled, and interference should be "massive" (e.g., the decrement caused when comparing baseline to automation in single task conditions should be doubled in dual task conditions). Second, the version of single resource theory proposed by Kahneman, is one that suggests that as demand grows, the capacity to supply additional resources to meet that demand will diminish. Hence any changes causing increased interference in single UAV conditions (e.g., going from automation to manual flight control), should cause substantially more interference in dual UAV conditions. Multiple resource theory does not make either of the above predictions.

Methods

Participants

Participants were 34 male and 2 female undergraduate students (ages 18-25) enrolled in the University of Illinois Aviation Program. All the participants had at least a private pilot's license, with some instrument flight experience. All participants received $8 per hour for their time. Participants were motivated to perform at their best with rewards of $10 and $5 for 1st and 2nd place finishes, respectively, in their group of six pilots.

Apparatus

The apparatus for the individual tasks was almost identical to Wickens and Dixon (2002). An Evans and Sutherland SimFusion 4000q, with dual 1.0 Ghz processors and an OPENsim Graphics card generated the UAV simulation. Each of the two UAVs was displayed on separate Hitachi CM721F 19-inch monitors, using 1280x1024 resolution. Figure M1 presents a sample display for a single UAV and Figure M2 shows the visual angles between tasks.
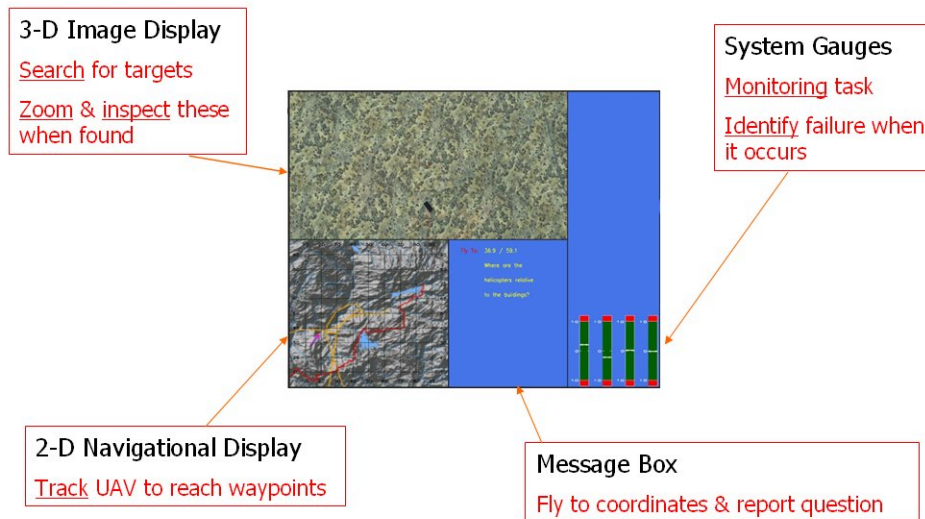

Figure M1. A screenshot example of the experimental display with verbal explanations for each task window. Actual display was larger and more legible than this rendering.
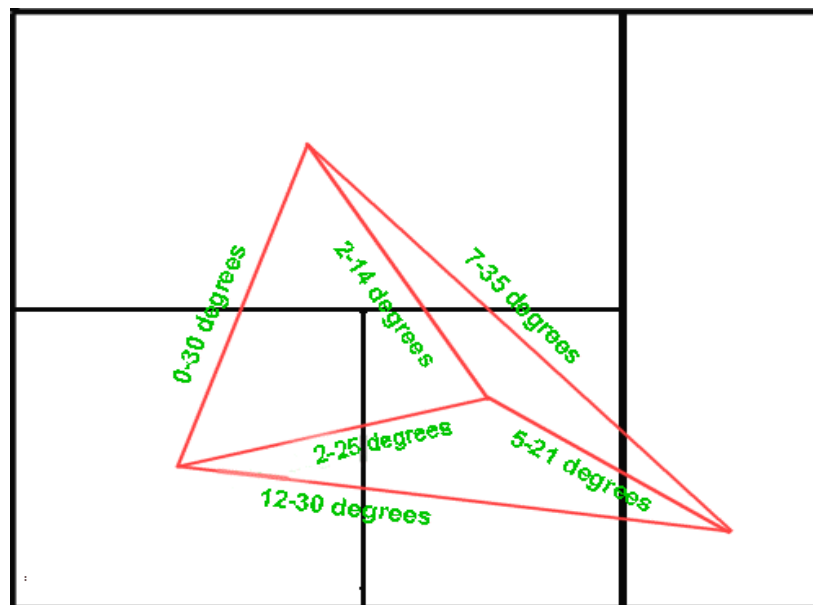
Figure M2. Range of visual angles between the four main windows / tasks. The ranges go from the two farthest points of interest to the two closest. The average visual angle is equal to the visual angle between the center points in the diagram.

As seen in Figure M1, the experimental environment was subdivided into four separate windows for each UAV. Figure M2 contains the range of visual angles between the individual windows. The top left window contained a 3D egocentric image view of the terrain forward and/or below the RPV. The sample figure shows a command target (CT) at normal viewing distance (i.e., 6000 feet altitude). The ability to manipulate this view depended on whether the operator was tracking a straight line path or loitering around a target. During regular tracking periods, the operator could view straight down to the ground or pan the camera up 45 degrees towards the horizon by manipulating the camera's y-axis. The momentary camera angle was indicated by a yellow dot along a red y-axis bar at the bottom center of the 3D window. During a loiter pattern, the operator was able to extend the viewing angle from 0 to 90 degrees along both the x- and y-axes. A zoom feature (up to 100x) was also available only in the loiter pattern.

The bottom left window contained a 2D top-down map of the 20x20 miles simulation world. Coordinates (which formed a grid) from 0-100 were placed along the x- and y-axes for navigation purposes. The yellow and red lines denoted minor and major roads, respectively. The smaller blue lines denoted rivers, and the large blue shapes denoted lakes.

The bottom center window contained the Message Box, with "fly to" coordinates and CT report questions. These instructions were present for 15 seconds at a time. During the Automation condition, the lower half of this box also contained a place to type in the coordinates for the next CT.

The bottom right window contained the four system failure (SF) gauges. Each gauge represented a different onboard system. The white bars oscillated up and down continuously, each driven by sine waves ranging in bandwidth from 0.01 Hz to 0.025 Hz. A SF occurred when one of the white bars moved gradually into a red zone.

Participants used a Logitech Digital 3D joystick to manipulate the aircraft/camera and a X-Key 20-button keypad with which to indicate responses. Each UAV had its own joystick and keypad. As seen in Figure M3, the joystick had controls for turning the UAV, manipulating the camera on the x- and y-axes, zooming, detecting targets, loitering around targets (to the left or right), and detecting SFs. The keypad was used for indicating which system failure occurred, the ownship coordinates for that system failure, and for typing in mission coordinates during the Automation condition. The experimenter used a separate keypad to record correct or incorrect responses and to indicate when the operator detected a target of opportunity (TOO) or a command target (CT).

Figure M3. Logitech joystick and X-Keys keypad.

Conditions and Tracking Task

There were three conditions: 1) Baseline, 2) Auditory, and 3) Automation. In each condition, the participants were seated approximately ½ meter away from the screen and required to fly two missions, each of which consisted of 10 legs with command targets at the end of each leg. One mission involved flying a single UAV and the other mission involved flying two UAVs simultaneously. Figure M4 shows a sample mission, highlighting the command targets and flight paths of the 10 legs. Each leg was approximately 10-12 kilometers long, and took approximately 5-8 minutes to complete. Each mission used a different set of legs and targets, so there were no repeating maps or targets for a participant.
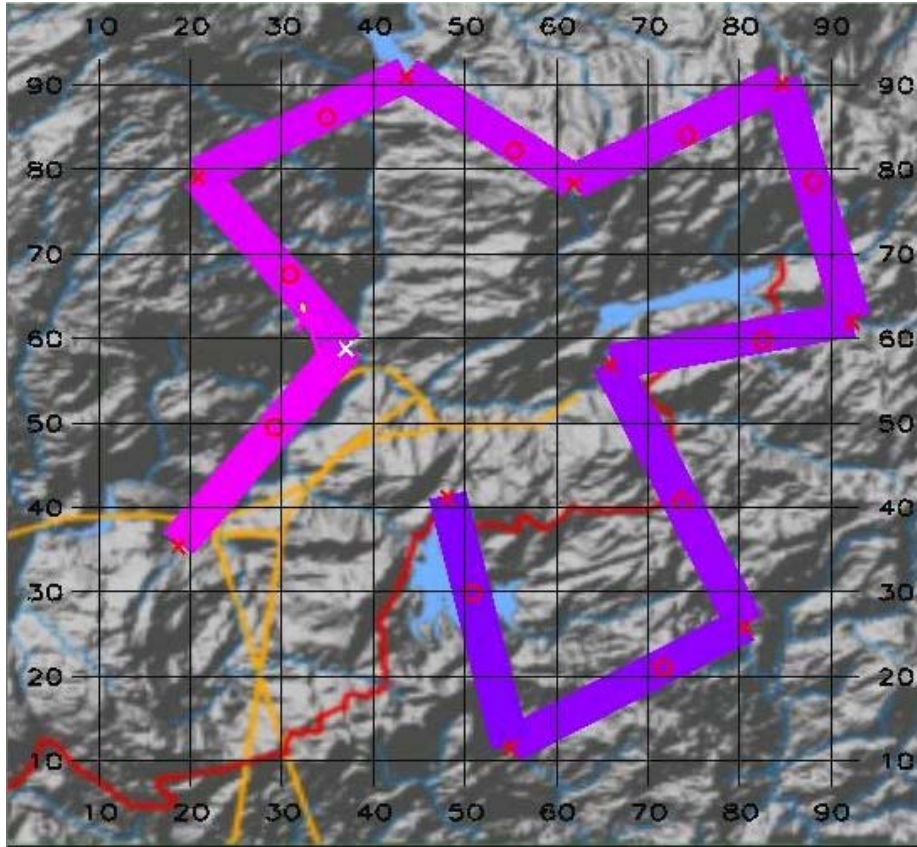
Figure M4. A sample mission. CTs are designated with red X's while TOOs are designated with red O's. This preplanned route was not shown to participants. The wide path along each leg indicates the width of the image in the 3D view when at minimum zoom.

There were two different forms of tracking control: 1) manual mode, and 2) automatic-mode. During the Baseline and Auditory conditions, the participants were required to manually control the UAV heading through each mission. This first-order control was accomplished by twisting the joystick to the left or the right. There was no disturbance in the control; that is, if left alone, the UAV would travel in the straight line established by the twist without deviation from its path. Participants were not responsible for airspeed (fixed at 70 knots), or altitude (fixed at 6000 feet). The operator did not have the capability to pitch, bank, or roll the UAV.

During the Automation condition, the operator was *not* responsible for manually tracking the UAV. Instead, he or she was required to type in the mission coordinates of the next command target at the beginning of each leg, using the keypad. The computer then automatically guided the UAV along a direct, straight-line path to those coordinates.

Both the Baseline and Automation conditions entailed visually reading all instructions and system parameters. The Auditory condition presented auditory instructions and alarms for system failures (see below).

Target Searching and Reporting Tasks

    A command target (CT) was located at the end of each mission leg, at the coordinates specified at the leg beginning. As seen in Figures M1 and M5, which depict a typical CT at 0x zoom and again at 100x zoom, respectively, these were very salient and easy to find. They consisted of a building (e.g., warehouse, factory, hanger, etc.) with 1-3 tanks and/or helicopters located within 10-50 feet around them. These weapons were always located on the north, south, east, or west sides.
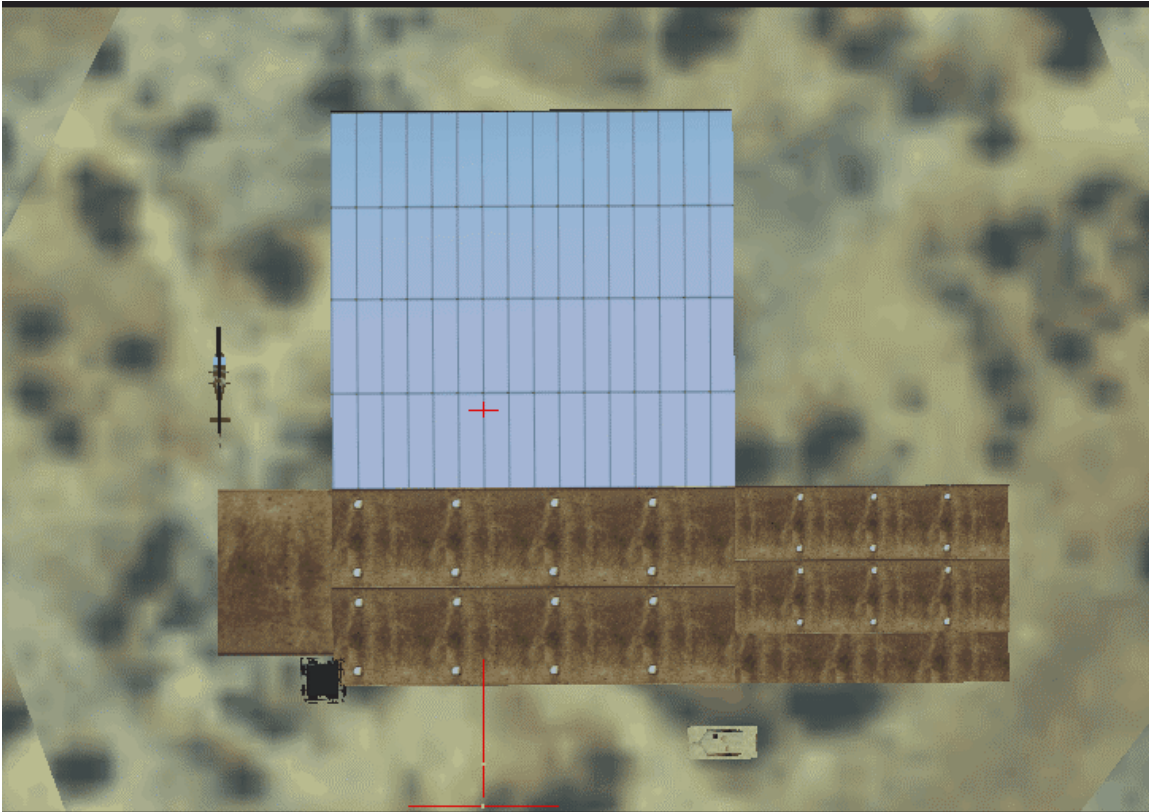
Figure M5. An example of a command target under a 100x zoom, from an angle looking straight down.

    The pilots were required to loiter around all CTs, zoom in the camera for a closer view, and respond to questions that appeared in the message box (or were spoken in the Auditory condition) about what they could see. Sample questions might be: 1) How many tanks are there and where are they located in relation to the building?, 2) Report the number of weapons present, or 3) Where are the helicopters located? These questions could only be answered once the operator had zoomed in close to the CT.

    These questions were offered once at the beginning of each leg and stayed visible in the message box for 15 seconds (in the manual and automatic modes) or were presented aurally by digitized speech in the auditory mode, lasting a duration of approximately 7-9 seconds. If the

pilots forgot the question, they were allowed to hit a Repeat button on their keyboard at any time. The number of repeats was recorded.

Along each leg, pilots were also instructed to search for Targets of Opportunity (TOO). Figures M6 and M7 depict a typical TOO at 0x zoom and again at 100x zoom, respectively. As seen in Figure M6, these TOOs were camouflaged and difficult to see at 6000 feet (i.e., zero zoom), and could not generally be detected unless foveated. All TOOs were the same basic square "bunker" shape and came in three sizes, with areas of approximately 1, 1.5, and 2 degrees of visual angle at zero zoom. There was one TOO per mission leg, which was located randomly somewhere in the middle 60% of each leg (i.e., between 20% and 80% of distance traveled); however, participants were not told this. They were only told that the TOO was somewhere along the direct-line path between CTs. Around each TOO were 1-3 tanks and/or helicopters, located within 10-30 feet of the bunker. These weapons were always located on the north, south, east, or west sides.

Figure M6. An example of a medium-sized TOO at 0x zoom. The TOO is located just below the arrow. On the actual monitor, the TOO was a bit easier to detect than in this printed display.
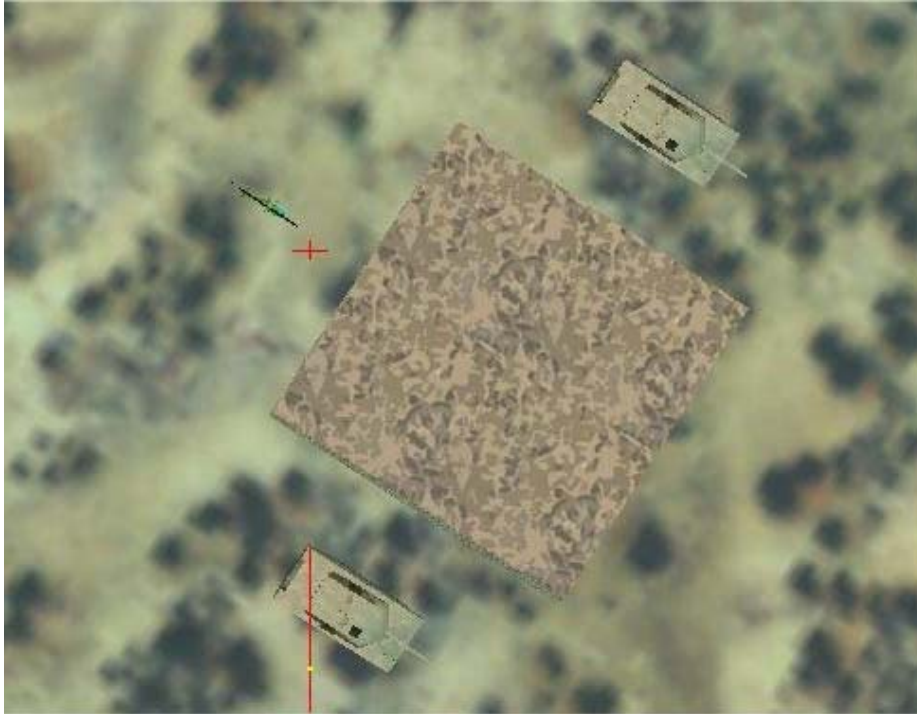
Figure M7. An example of a Target of Opportunity (TOO) under a 100x zoom.

The question for TOOs was always the same: "what weapons do you see and where are they located?" Location was to be specified in cardinal directions, thereby forcing a relatively high level of spatial-cognitive activity (e.g., Gugerty & Brooks, 2001). As with the CTs, these questions could only be answered once the operator had zoomed in close to the target.

If the participant detected a CT or TOO, he or she was required to indicate detection by pulling the joystick trigger. The experimenter then pressed the appropriate button on the experimenter's keypad to indicate whether this was a TOO or CT. After deciding that the UAV was close enough to the target to begin inspection, the participant pressed the loiter button (loiter would be selected either left or right) on the joystick (see Figure M3). This put the UAV into an automated oval pattern around the target. This oval pattern was 1.3 kilometers wide and 2.1 kilometers long, and took between 2.5 to 3 minutes to complete an entire 4.8-kilometer circuit. The UAV turned 3 degrees per second at the ends of the oval. During the loiter pattern, the participant was able to use the x- and y-axes of the camera, as well as to zoom in and focus more closely on the target. The task of keeping the TOO in view while zooming *and* moving *and* keeping track of cardinal directions, was extremely challenging.

After making the report, the participant could then depress the loiter button again, which would unloiter the UAV and unzoom the camera, returning the egocentric view to 6000 feet altitude. In the Baseline and Auditory conditions, once the report was completed, the participant had to relocate CT coordinates and reorient the UAV to the direct path to the CT. In the Automation condition, the UAV automatically resumed the correct path to the next CT. The duration of time between detection and completion of the final report was recorded as the response time measure. There was no separate measure of detection time (i.e., the time between

the appearance of the TOO on the screen, and the pilot's depression of the "detect" button), since the former event was difficult to establish on a case by case basis, given variability of the course, and the camera angle.

System Monitoring Task

During each mission, participants were also asked to detect system failures (SF). A SF occurred when a system gauge needle went out of bounds (i.e., passed from the green zone into the red zone at either the top or bottom of the gauge; see Figure M1). Each SF lasted approximately 30 seconds before automatically resetting (i.e., moving back into the green zone) if not detected. Not every leg contained a SF, and no leg contained more than one SF, although participants were not told this. The number of correct detections and the time it took to detect the SFs were recorded.

If a SF was detected, the participant pressed a "detect" button on the joystick. Then he or she pressed the appropriate button on the keypad to indicate which system had failed. Lastly, the pilot typed in current ownship coordinates and then hit Enter. The duration of this time between detection and final report completion was recorded.

The SFs were categorized under 4 types: A) during initiation of flight heading (i.e., while the pilot was consulting the message box and the 2D map, deciding how to turn the plane, and establishing the correct course); B) during regular flight, when no TOO was visible; D) approximately 5 seconds after a TOO loiter pattern was entered (i.e., the TOO had been detected and image inspection had begun); E) approximately 5 seconds after a CT loiter was entered. These will be referred to below as SF_A, SF_B, SF_D, and SF_E. Figure M8 shows a typical mission leg and the locations where SFs might occur along the leg.
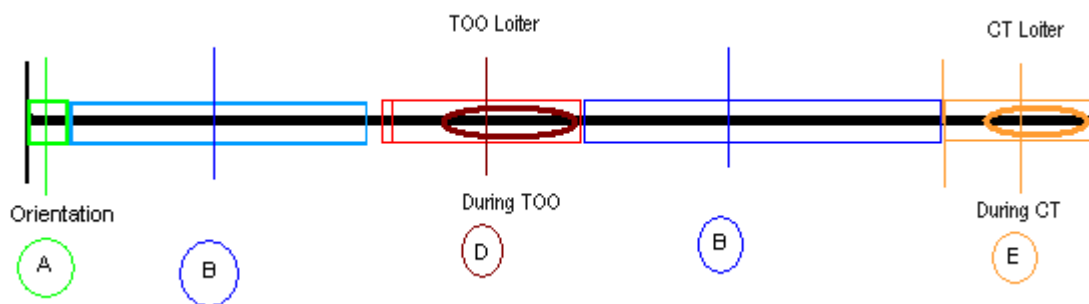

Figure M8. A timeline of SFs for a typical mission leg.

Procedure

Each participant was seated in a comfortable chair in front of the mission monitor. After signing the consent form, participants were asked to read the instructions for the experiment. Once they completed the instructions, they were allowed to spend 10-12 minutes on a practice mission, during which they would be exposed to two CTs, two SFs, and one TOO. Any questions they might have were answered by the experimenter. Once the practice mission was completed,

the participants were asked if they felt comfortable with the controls and instructions. All the participants responded positively and none of them asked for more time.

The experimenter then started the first mission. Immediately, the instructions (i.e., "fly to" coordinates and CT question) for the first mission leg were posted visually (for Baseline and Automation conditions) in the Message Box, or aurally (for the Auditory condition). Throughout each mission, the participants were free to choose their own strategies for target search and systems monitoring. They were allowed to complete each task in the order they chose. While they were instructed to give equal priority to all tasks, at no time during the missions were they critiqued if they decided to give one task more priority than another. During dual-task situations, pilots were able to choose their own method of handling concurrent tasks; that is, they were free to serially process or parallel process as they saw fit.

Design

A mixed-subjects design was employed, in which all 36 participants were exposed to one of the three conditions in both a single- and dual-UAV scenario. The number of UAVs and mission maps were counterbalanced. Since there were three different maps (A, B, & C), defined by their legs, target locations, and target types, these were crossed with display condition and number of UAVs.

Dependent variables included: 1) tracking error; 2) detection rates, response times, and accuracy for SFs and TOOs; 3) response times and accuracy for CTs; and 4) repeats (i.e., requests for repeated viewing or hearing of the CT instructions).

To review, there are four human information processing tasks for which the pilot is responsible; 1) tracking, 2) monitoring for TOOs, 3) monitoring for SFs, and 4) memory task (of the CT location and instructions). These four tasks can be collapsed into three major goal-oriented tasks: 1) navigation task, 2) TOO task, and 3) SF task. The three goal-oriented tasks are shown in Table M1. Each task is broken down into a series of subtasks, that typically appear in sequence.

Table M1. Task analysis.

1. Navigation Task:
    1.1 Read (or hear) CT location
    1.2 Establish coordinates (by orienting vehicle by joystick control or typing)
    1.3 Monitor heading toward CT location on 2D map (and re-orient if necessary)
    1.4 Refresh memory for location and final report
    1.5 Inspect image
        1.5.1 Enter loiter
        1.5.2 Zoom in
        1.5.3 Adjust camera orientation
        1.5.4 Count identify and/or assess cardinal orientations
        1.5.5 Verbal report of content.

2. TOO task:
    2.1 Monitor 3D display
    2.2 Inspect image if target located
        (see 1.5 for subtasks)

3. System Failure Task:
    3.1 Monitor for System failures
    3.2 Identify failure
    3.3 Keyboard data entry

Results

This results section has been divided into six main subsections. The first three subsections correspond to the three goal-oriented tasks discussed in the Methods section, while the last three subsections deal with inter-workstation timelines, subjective pilot ratings, and IMPRINT modeling. The Discussion section will be used to establish and explain the relationship between the various subsections and how they contribute to model testing and validation.

For the most part, mixed-design statistics were employed to analyze the data; however, due to missing data points in some performance measures (e.g., if a target is not detected, then the corresponding SF will never occur), a between-subjects analysis was conducted to save the remaining data. The between-subjects analysis is generally a more conservative approach.

In general, our interests lay in analyzing the effects of the two offload conditions (baseline and automation) when compared to the baseline condition. These two planned comparisons were developed prior to running subjects, so there were no adjustments made (e.g., Bonferroni) to control familywise Type 1 error rates (see Keppel, 1982, for a more detailed explanation of this approach). Furthermore, one-tailed t-tests were frequently used because we expected improvements due to the two offloads.

Because the current experiment included a single-UAV flight control, the results often replicated previous findings (see Wickens & Dixon, 2002). However, because of the added

incentives and subsequent increased effort, there are differences between the experiments that are highlighted in this section.

Lastly, the current study originally included a SF_C, which was designed to occur just before a TOO appeared on the 3D display; however, due to programming issues, these SFs did not measure precisely what they were intended to measure. Because they were still legitimate SFs, the data were included in overall ANOVAs, but because of their temporal uncertainty, they were not included in more detailed comparisons between conditions and SF types.

In the first three sections, we analyze the main objective performance measures: 1) mission completion, 2) target of opportunity (TOO) analysis, and 3) system failures (SF). Table 1 presents an overview of the data from all tasks across both single- versus dual-UAV flight control and the three flight conditions.

Table 1. Performance data for all major tasks.

	Single			Dual		
	Baseline	**Auditory**	**Automation**	**Baseline**	**Auditory**	**Automation**
Tracking Error (RMS - meters)	2785	2775	0.00	2796	2766	0.00
CT Response Time (secs)	28.77	21.85	21.23	29.06	26.91	25.58
CT Accuracy (%)	86	86	89	92	78	88
Number of Repeats (per leg)	2.90	1.78	1.50	41.63	31.25	18.88
TOO Detection Rate (%)	57	45	92	40	28	79
TOO Report Time (secs)	18.84	19.87	18.85	22.32	20.97	17.42
TOO Report Accuracy (%)	79	75	89	77	71	90
SF Detection Rate (%)	85	92	93	73	98	83
SF Detection Time (secs)	7.16	3.58	8.31	10.91	3.91	11.19
SF Correction Time (secs)	11.40	9.44	11.80	10.72	9.76	11.09
SF Report Accuracy (%)	90	93	93	90	97	88

1.0 Mission Completion

As in the previous study, tracking again benefited from automation (zero error). A mixed-design analysis of variance revealed that tracking did not benefit from the auditory offload [F(1, 22) < 1.0]. Furthermore, tracking error in the dual-UAV scenario was essentially equivalent to single-UAV flight across both baseline and auditory conditions [F(1, 22) < 1.0]. This suggests that pilots placed primary importance on the tracking task and allocated enough resources to that task to ensure its successful completion regardless of conditions or number of UAVs. This resource allocation policy presumably eliminated any benefit provided by offloading concurrent task to the auditory channel.

Response times to command targets (CT) were essentially equivalent across conditions [F(2, 33) = 1.09, p = .35], and number of UAVs [F(1, 33) = 2.2, p = .15], with no interaction between load and condition [F(2, 33) < 1.0]. However, the raw data suggests a trend towards larger report times in dual-UAV flight control, when some attention may need to be diverted to

monitoring the other UAV. CT report accuracy followed the same pattern [F(2, 33) = 1.86, p = .17; F(1, 33) < 1.0], suggesting that neither offload nor number of UAVs had any effect on completion of the report task. Again, pilots appeared to treat this task of fulfilling the mission command objectives as primary, safeguarding it against workload demands.

During each mission leg, pilots were required to read and memorize fly-to coordinates and report questions. If necessary, they were able to refresh their memory by pressing a repeat button, which would trigger another 15-second presentation of the flight instructions (played one time in the auditory condition). Figure R1 presents the number of repeats summed over the 10 legs during each of the six possible conditions.
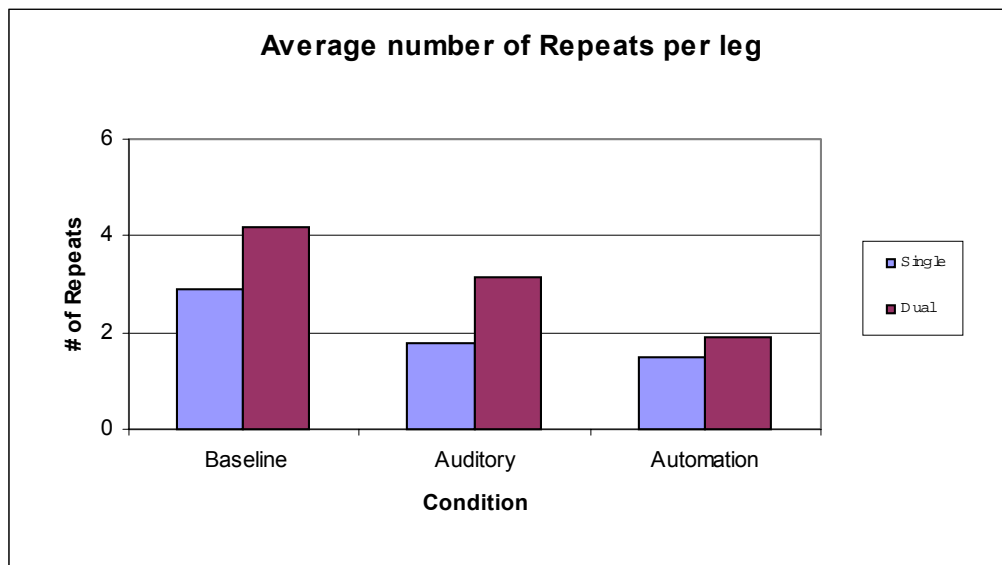
Figure R1. Average number of repeats per leg across conditions and number of UAVs.

As in Experiment 1, the auditory condition led to fewer repeats when compared to the baseline condition [F(1, 22) = 7.78, p = .01], regardless of the number of UAVs, as seen in the lack of an interaction effect [F(1, 22) < 1.0]. This was presumably because pilots were able to offload some of the visual demands to the auditory channel. In the baseline condition, pilots had to divide foveal attention between all the different windows. Because of the wide visual angles between these areas of interest (7 – 23.5 degrees on one UAV workstation), parallel processing is effectively prevented. By relieving the pilot of having to read flight instructions while monitoring other visual displays, visual scanning became less likely to create interference, and resulted in improved performance, a benefit that was equally realized in both single and dual UAV conditions.

Figure R2 presents a timeline of repeats for a sample mission leg. Each mission leg is divided into sections representing a particular percentage of leg completion. Most evident from the figure is the frequent use of the repeat button early in the leg, as pilots are presumably assuring their correct identification of the CT coordinates and path to be flown, and again later in the leg, as pilots are refreshing the report question for the CT. The figure also reveals that the

auditory condition appears to improve performance throughout the mission leg, particularly in single-UAV flight control. In dual-UAV flight control, the benefit is more apparent at the beginning and end of each leg, indicating less need to initially refresh the fly-to coordinates and also less need to refresh the report question just prior to entering a CT loiter.
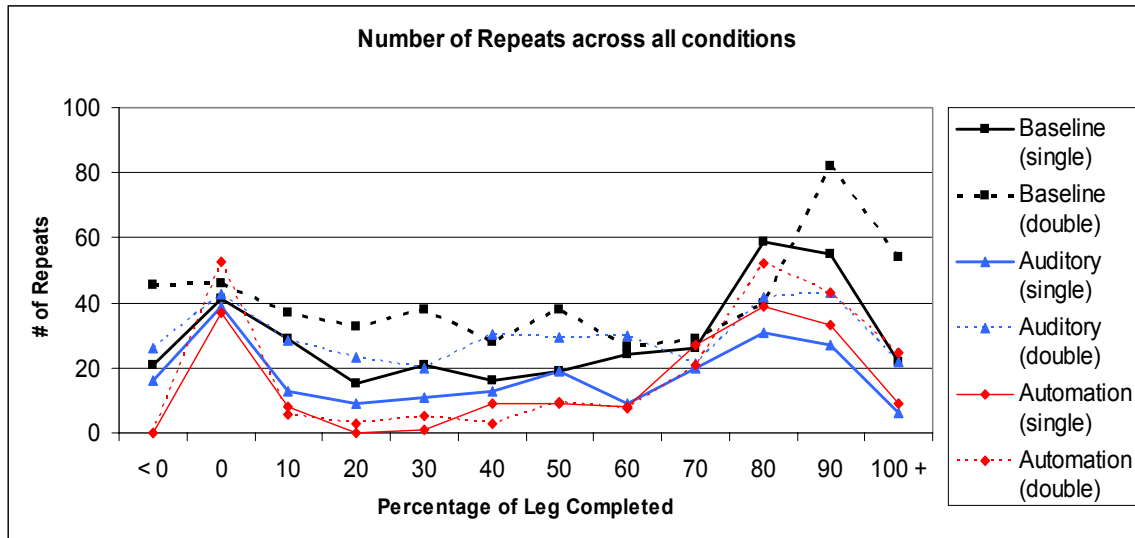

Figure R2. A timeline of repeats for a sample mission leg. Negative values indicate repeats during periods of time when the pilot is initiating heading in the wrong direction, and values over 100% indicate CT overshoots.

Automation also led to fewer overall repeats $[F(1, 22) = 27.28, p < .001]$ than the baseline condition, but for different reasons than the auditory offload. As seen in Figure R2, the reduction in repeats was most apparent in the middle of the mission legs, indicating that pilots felt no need to refresh fly-to coordinates since they knew the auto-pilot would guide them correctly to the next CT. However, a spike in the number of repeats both during the initial heading and just prior to a CT loiter indicates that pilots did not benefit as much from automation when they were trying to *input* fly-to coordinates or *recall* report questions, although there is some improvement over the baseline condition.

As both figures show, the number of repeats increased dramatically during dual-UAV flight when compared to single-UAV flight $[F(1, 33) = 43.18, p < .01]$. This dual-UAV decrement is not as severe in the automation condition as in the other two conditions, as reflected by the condition x load interaction $[F(2, 33) = 4.08, p < .05]$, a difference which can be explained by the lack of need to refresh fly-to coordinates during automated flight control regardless of the number of UAVs.

2.0 TOO monitoring

Figure R3 presents the percentage of TOOs detected on average throughout each mission. A mixed-design analysis of variance indicates a strong main effect for condition $[F(2, 33) = 18.29, p < .001]$ on TOO detection rates. However, this effect only appears to be manifest when

comparing baseline results to automation. A comparison between the baseline and auditory conditions [$F_{(1, 22)} = 1.47$, $p = .24$] reveals that auditory offloading had no effect on TOO detection rates.

TOO Detection Rate

Figure R3. TOO detection rate across conditions and number of UAVs.

By contrast, the automation condition facilitated a much greater TOO detection rate than the baseline condition [$F_{(1, 22)} = 24.96$, $p < .001$], equally so in both the single- and dual-UAV flight controls, as evidenced by a lack of interaction between condition and number of UAVs [$F_{(1, 22)} < 1.0$].

As in the previous experiment, there appear to be two explanations for this effect. First, the auto-pilot, by nature, always guided the UAV in a direct, straight-line path to the next CT, thus ensuring that all TOOs would appear in the 3D display. In the baseline condition, tracking error sometimes prevented pilots from having the opportunity to detect TOOs. However, even when comparing results of TOOs that actually did appear in the 3D display during both conditions, there is still an improvement in TOO detection rates for the automation condition. In the single-UAV flight control, of the 73% of TOOs that came into the 3D display during the baseline condition, only 76% were detected, as compared to 92% for the automation condition [marginally significant gain of 16%: $t_{(11)} = 1.87$, $p < .10$]. In the dual-UAV flight control, of the 68% of TOOs that came into the 3D display during the baseline condition, only 52% were detected, as compared to 79% for the automation condition: a significant gain of 27% [$t_{(11)} = 3.31$, $p < .01$]. This suggests that a second reason for improved detection must exist; that is, the auto-pilot was able to allow reallocation of perceptual, cognitive, and motor resources, originally used for manual tracking, to the TOO detection task.

TOO detection rates dropped about 10-20% when adding a second UAV workstation, [$F_{(1, 33)} = 20.01$, $p < .001$], with decrements that were relatively equal across all three conditions, [$F_{(2, 33)} < 1.0$]. This suggests that increased visual angles between the tasks resulted in decreased ability to foveate on the necessary displays. Furthermore, as seen below in the

timeline analysis, TOOs sometimes occurred simultaneously on both workstations, increasing the difficulty level of detection.

Figure R4 presents the TOO report times across conditions and number of UAVs. An overall analysis of variance reveals no statistically significant differences between condition or number of UAVs for TOO response times.

TOO Report Times

Figure R4. TOO report times across conditions and number of UAVs.

While the single-UAV results do appear equivalent across conditions, a dual-UAV post hoc comparison between the baseline and automation conditions reveals a marginally significant difference in response times [$t(21) = 1.86$, $p < .05$], with an almost 5-second advantage for the automation condition. This can be explained by the simple fact that pilots did not need to monitor the tracking task in one workstation while dealing with TOOs in the other workstation during the automation condition. In contrast, visual and motor demands of tracking in the baseline condition would almost certainly interfere with visual and motor demands in the TOO inspection and report task.

With regards to TOO report accuracy, a mixed-design analysis of variance revealed no main effects for either condition [$F(2, 33) = 1.30$, $p = .29$] or number of UAVs [$F(1, 33) < 1.0$]. This is consistent with the report accuracy results found for CTs.

3.0 System Failures

In the previous experiment, the auditory condition was found to improve SF detection rates and facilitate shorter response times for SFs which occurred during relatively routine concurrent tasks (i.e., SF_A and SF_B), but not during SFs which occurred in conjunction with highly challenging tasks (i.e., SF_D and SF_E). The assumption was made that pilots were forced into "cognitive tunneling" because of the difficulty of the target inspection task. To overcome this single channel tunneling, pilots in the present experiment were rewarded with monetary

35

prizes for exceptional performance. It was hypothesized that increased rewards would lead to equal increased effort, thus resulting in improved parallel processing during the auditory condition. Figure R5 presents SF detection rates for the six conditions.
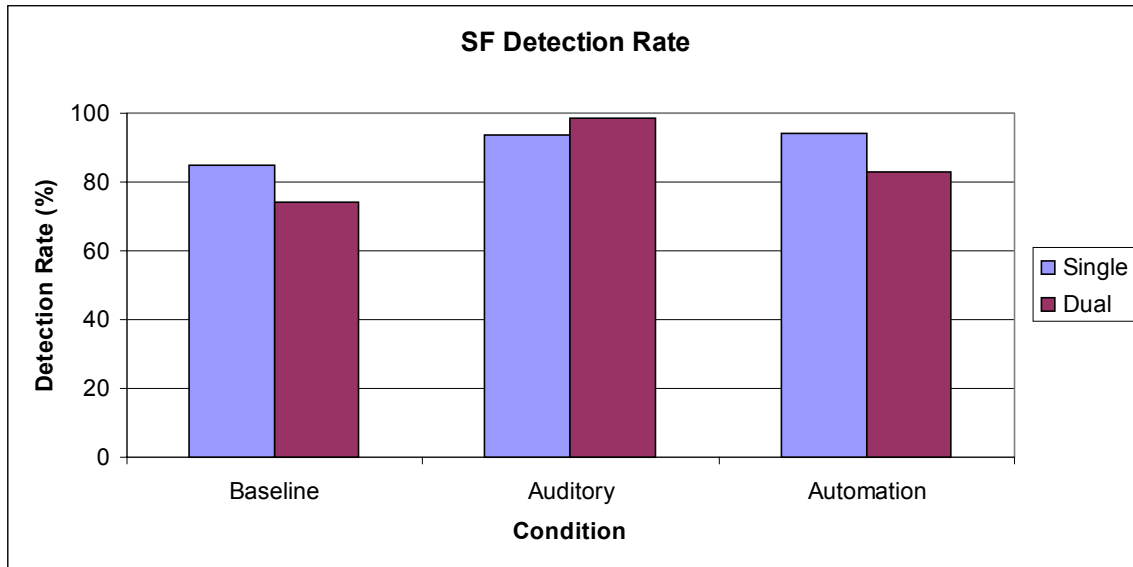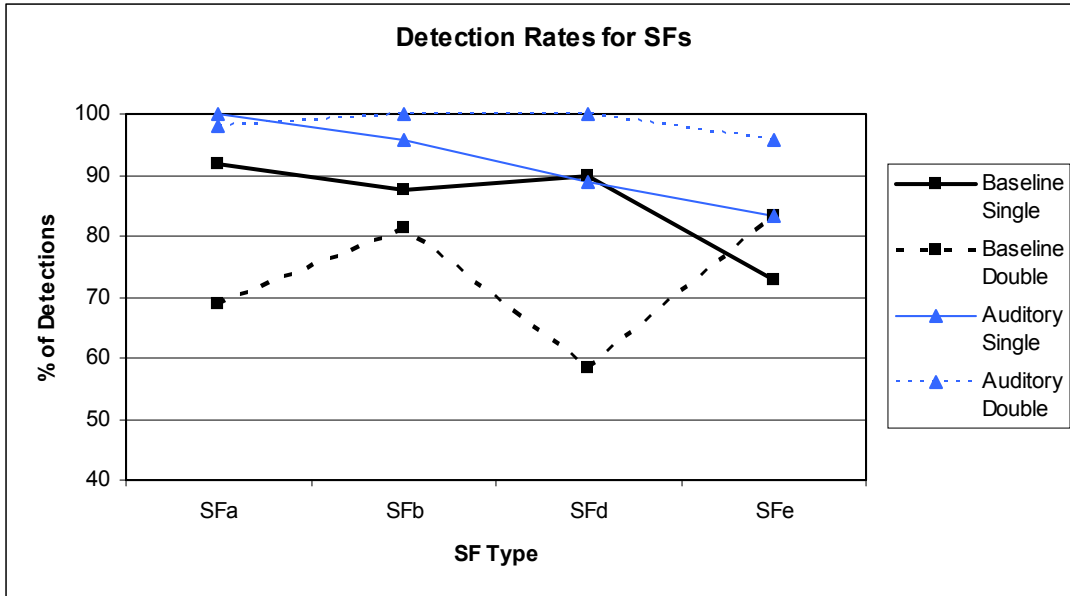

SF Detection Rate

Figure R5. Overall SF detection rates across conditions and number of UAVs.

A mixed-design analysis of variance between the baseline and auditory conditions shows a main effect for condition [$F(1, 22) = 5.29$, $p = .03$], but not for number of UAVs [$F(1, 22) <$ 1.0]. The lack of interaction between condition and number of UAVs [$F(1, 22) = 1.70$, $p = .21$] suggests equally improved detection rates in both the single- and dual-UAV flight controls when the SFs were offloaded to the auditory channel. Further statistical analyses between specific SF types were unrealistic due to the paucity of individual data points and the resulting lack of statistical power. However, Figure R6a presents this breakdown of the SF types in order to show patterns in the data which suggest that the auditory condition did not suffer across SF type as seen in Experiment 1. In fact, detection rates in the auditory condition approached perfect performance for almost all of the SF types. Most importantly, the decrement in detection of SF_D and SF_E, which in the previous experiment were seen as symptoms of cognitive tunneling, were not observed here. This pattern is almost certainly not the case for the baseline condition, which fell well below 90% in most cases, particularly in the dual-UAV flight control.

Figure R6a. SF detection rates across SF types, conditions, and number of UAVs.

A mixed-design analysis of variance between the baseline and automation conditions shows no main effect for condition [$F(1, 22) = 1.38$, $p = .26$], and a marginally significant effect for number of UAVs [$F(1, 22) = 3.28$, $p = .08$]. Further paired comparisons between the single- and dual-UAV flight controls in the baseline condition [$t(11) < 1.0$], and the automation condition [$t(11) = 2.20$, $p < .05$], show this dual-UAV decrement to be present only in the automation condition. Figure R7 reveals that this dual-UAV decrement only appears to show up in two of the four SF types for the automation condition.
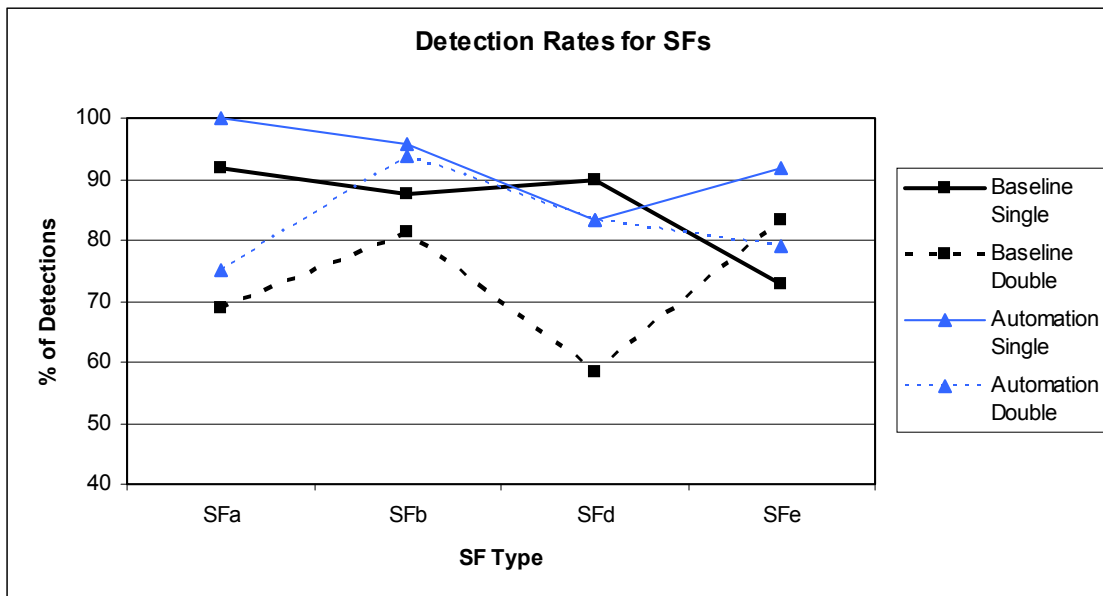
Figure R6b. SF detection rates across SF types, conditions, and number of UAVs.

In contrast to the previous experiment, SF response times in the current experiment were divided into two subsections: detection times and correction times. Detection times indicate how long it took the pilot to notice the SF and press the detection button, while correction times indicate how long it took to actually diagnose and correct the SF and input the current UAV coordinates.

Figure R7 presents the overall SF detection times collapsed across SF type. A between-subjects analysis of variance for detection times revealed an overall main effect of condition $[F(1, 294) = 35.54, p < .001]$; however, planned comparisons between the baseline and offload conditions showed this effect to only be present when compared to the auditory condition $[F(1, 188) = 54.37, p < .001]$, and not to the automation condition $[F(1, 195) = 1.06, p = .30]$.
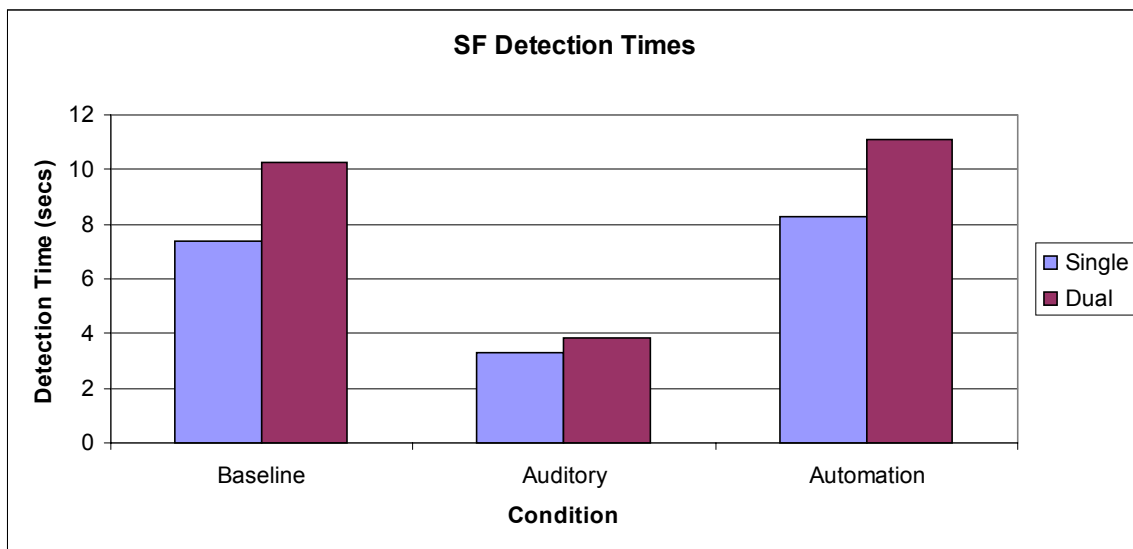
Figure R7. Overall detection times across conditions and number of UAVs.

Figure R7 reveals that the auditory condition facilitated detection times that were less than half as long as the baseline condition. Furthermore, the dual-UAV decrement that once again shows up in the baseline $[F(1, 89) = 4.05, p < .01]$ and automation $[F(1, 106) = 5.42, p < .05]$ conditions is not present in the auditory condition $[F(1, 99) = 1.66, p = .20]$. This finding is consistent with the detection rate data which shows that the auditory condition does not suffer when adding an addition UAV workstation.

Figure R8 presents detection times broken down according to SF type. Two important features immediately arise from this graph. First, as reflected by the two lines at the bottom of the graph, not only does the auditory condition support overall equal performance between single- and dual-UAV conditions, but this trend appears to be consistent across all SF types $[p > .05$ for all single-dual comparisons]. The results show this is not always the case for the baseline $[SF_A: p < .05; SF_B: p < .05]$ or automation $[SF_B: p < .01]$ conditions.
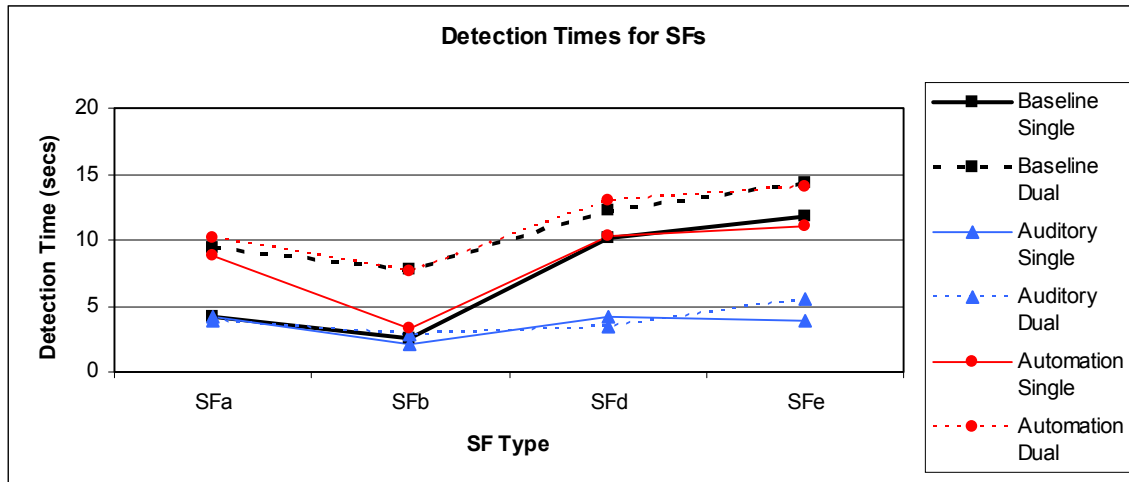
Figure R8. SF detection times across SF types, conditions, and number of UAVs.

Secondly, while there is a strong *statistical* effect of SF type [$F(4, 99) = 3.80$, $p < .01$] in the auditory condition, due to very low variance, this effect is not *practically* strong. The largest difference between SF types appears to be only 2-3 seconds, while the baseline [$F(4, 89) = 4.16$, $p < .01$] and automation [$F(4, 105) = 3.70$, $p < .01$] conditions reveal much larger 3-11 second differences. This suggests that the cognitive tunneling effect found in the prior experiment is not nearly as strong in the current experiment for the auditory condition; that is, when combining a SF task with the highly difficult task of target inspection (i.e., SF_D and SF_E), performance in SF detection does not appear to suffer when compared to a SF combined with an easier concurrent task (i.e., SF_A and SF_B). This lends credence to the theory that cognitive tunneling may be more of a strategic effect rather than a structural one. In other words, pilots tend to process serially out of choice, and not out of necessity. By offering incentives, as we did in the current experiment, this strategic tunneling can be overcome.

SF correction times were measured by how long it took to correct and report the location of the SF. A between-subjects analysis of variance revealed no main effects for condition when comparing the baseline condition to the auditory [$F(1, 189) = 1.98$, $p = .16$] or the automation [$F(1, 196) < 1.0$]. These results are expected since all conditions are essentially equal once the SF has been detected. Although there might have been a slight reduction in workload in the dual-UAV automation condition because pilots were not required to manually fly the UAV, this advantage would have been very small indeed because once the initial heading had been set, the UAV flew a straight-line course free of turbulence. Because of this, pilots did not need to concern themselves with checking the flight path of the UAV during the short window of time it took to diagnose and correct a SF.

4.0 Timeline Analysis

The purpose of the timeline analysis in the current study is to examine the effects that performing tasks on one UAV workstation has on tasks in the other workstation. In this section, the focus of analysis was to determine exactly when a certain type of task was occurring on both

workstations simultaneously, and then to compare how each of the offloads might have improved this dual-task performance. The tasks that were compared included: SFs, TOOs, and CTs on both workstations. These were paired up in the following ways: TOO + SF, TOO + TOO, TOO + CT, CT + SF, CT + TOO, CT + CT. The pairs were analyzed for both left and right workstations, resulting in a total of 36 combinations (6 pairs x 2 workstations x 3 conditions). Figure R9 presents the overall data collapsed across all pair, workstations, and conditions.
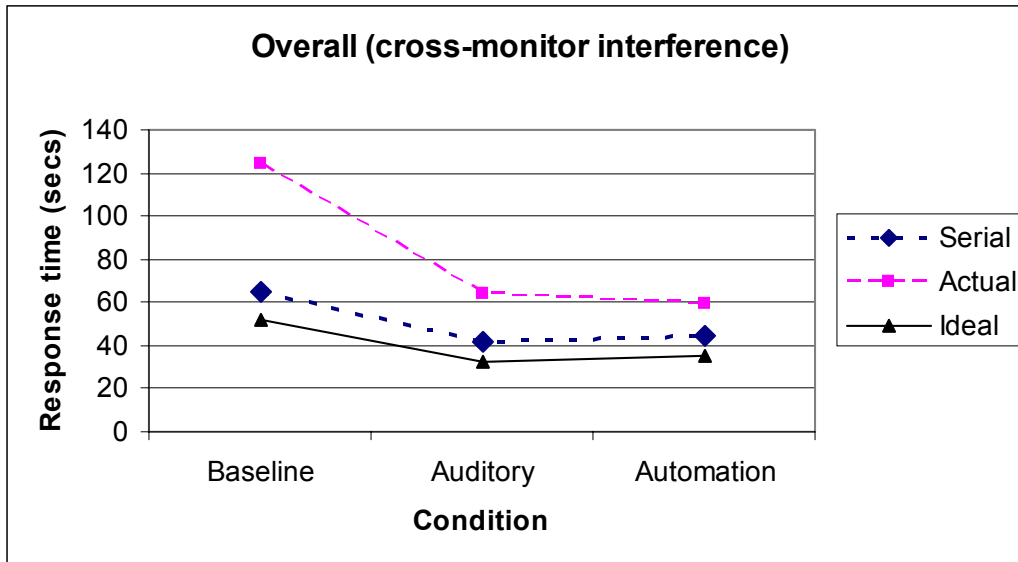
Figure R9. Overall response times to pairs of tasks.

In Figure R9, the "serial" value indicates how long the response *should* be if single channel serial processing took place; that is, the sum of the two average task times for that pilot, as each task time was computed when the task was performed without a task (other than monitoring) done on the other workstation. The "ideal" value indicates how long it should take if perfect parallel processing took place; that is, if both tasks were done simultaneously with no task interference. The "actual" value is how long it actually took the pilot to perform both tasks in their entirety.

From the graph, it is apparent that the actual times for most tasks was greater than the sum of the two average task times, thus suggesting a pattern of switching costs between tasks. Pilots were apparently trying to switch back and forth between tasks, costing them additional time, when it might have been more efficient to simply complete one task before beginning the other. It is also evident from the graph that this cost was much greater in the baseline condition than in the auditory [t(25) = 3.01, p < .01] or automation [t(30) = 4.34, p < .001] conditions. This effect is not surprising, since automation reduces the need to monitor the flight path and the auditory offload reduces the need to monitor the SF display.

It should be noted, however, that these results are diluted somewhat by including combinations of tasks that do not inherently benefit the auditory condition. For example, TOO + TOO combinations are probably not as likely to improve in the auditory condition as TOO + SF

combinations. Figures R10 and R11 present data separately for TOO + SF and CT + SF combinations, respectively.
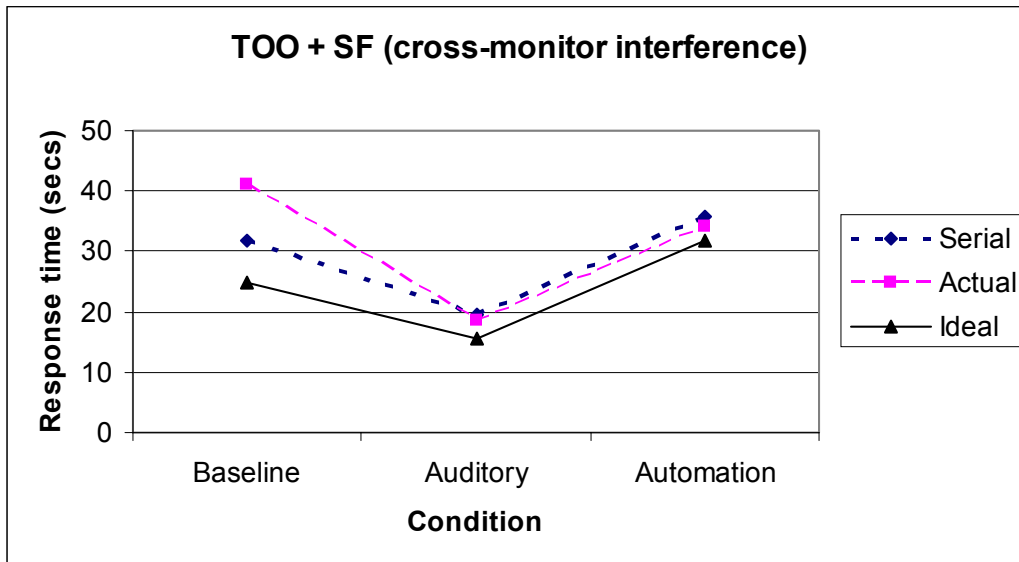

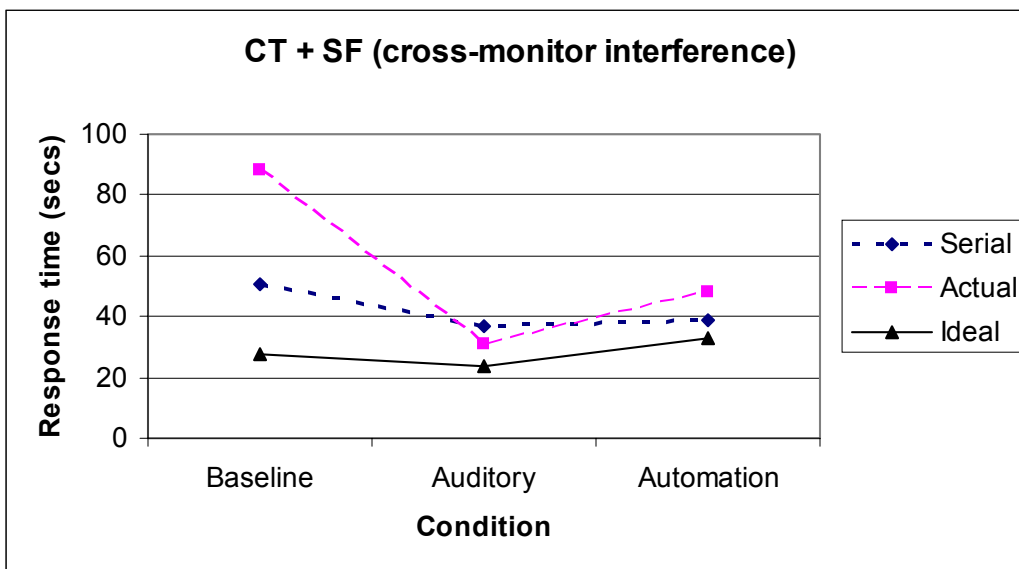Figure R10. Response times to TOO + SF combinations across workstations.

Figure R11. Response times to CT + SF combinations across workstations.

The results from Figures R10 and R11 show a more salient improvement in the auditory condition over the baseline condition with respect to parallel processing. While the paucity of data points prevents a statistical comparison, it is obvious that during the few opportunities that pilots had to dual-task (target inspection plus SF) across workstations, they were able to parallel process when offloading the SF task to the auditory channel. This is suggested because in the

auditory condition, the "actual" performance is better than the "serial" performance. In contrast, pilots performed 2-3 times *worse* than ideal in the baseline condition. This finding is expected, given that the visual angles between these tasks (the two display workstations) was over 30 degrees, which, in most cases, requires head movement to switch between tasks.

The automation condition also facilitated improved performance across workstations when compared to the baseline condition, suggesting a similar pattern with data in the same workstation. Time (SCT) and mental resources (SRT and MRT) saved by not having to manually track in the automated condition were reallocated to the task combinations discussed here. The latter data provide an interesting convergence with the findings of Liao and Moray (1993), whose modeling efforts revealed evidence for parallel processing with two tasks, but not with four. Although the mapping between their tasks and ours is far from perfect, the current data also suggest that when three active tasks were required (tracking on one workstation with SF and TOO inspection distributed across both workstations), parallel processing was disabled in the baseline condition. But when tracking was automated, and the tasks were thereby reduced to two, evidence for parallel processing reemerges.

Another prediction of strict SCT, outlined in the introduction, was tested by assessing the delay by which a second-arriving task event arrived following the initiation of a first-arriving task, when the former arrived before the latter was completed. According to the SCT predictions, unless there is switching between tasks, every one-second shortening of this arrival delay will produce a concomitant one-second lengthening of response time to the second-arriving task (RT_2). In Figure R12, these values of RT_2 are plotted against the arrival delay for the total sample of data points in which there was task time overlap between the two tasks, one present on each workstation.
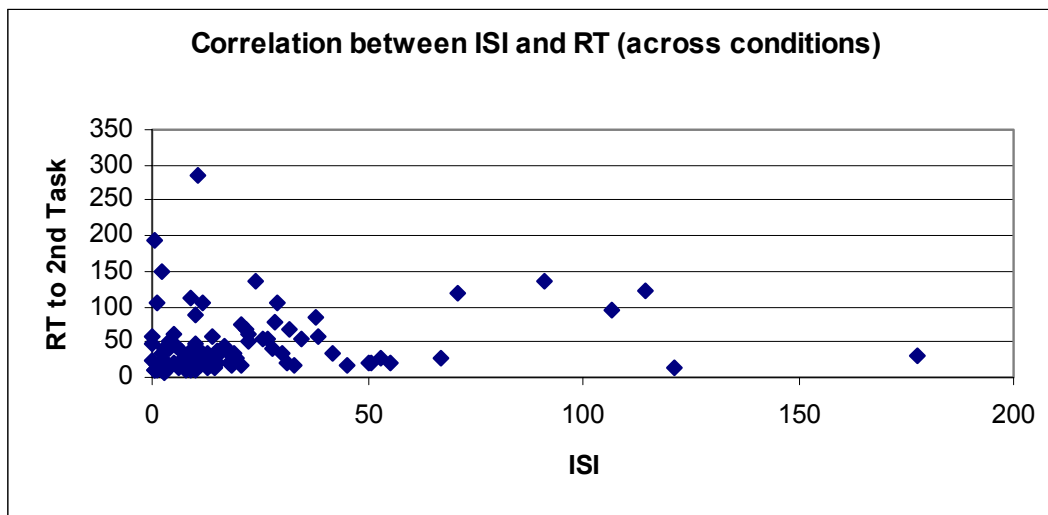

Figure R12. Correlation between interstimulus interval (ISI) and RT to the secondary task. The data is collapsed across all conditions.

The data in Figure R12 reveal no evidence for the negative correlation, with a slope of -1, that strict SCT would predict (r = 0.13), and so are inconsistent with a strict single channel

model, by which engagement of a cognitive process on one UAV workstation will totally "lock out" the initiation of performance on second UAV workstation until the former is complete. Similar results were obtained when breaking the data down into separate dual-task pairs (e.g., CT vs. SF; TOO vs. SF, etc.). The present analysis does not, however, reject all forms of single channel theory. For example, they could be consistent with a switching model in which attention is switched immediately to the later arriving task, and the ongoing task bears the cost of concurrence and delay.

A subsequent analysis on RT to the first arriving task revealed that its performance time was actually shortened, rather than lengthened, as the inter arrival time decreased, showing a significant positive correlation of 0.68. We interpret this finding to mean that, if a task arrived on one work station shortly after the pilot initiated performance on the other, the pilot accelerated performance on the latter task (perhaps by mobilizing more effort) to deal with the imposed dual task demands.

5.0 Single Resource Theory Predictions.

In Table 2 we presented the predicted demand value of various component tasks. According to a pure version of single resource theory, the interference between tasks should be a direct function of their task demand value. In order to test these predictions, the **total concurrent demand value** of each single and dual task combination was computed, simply by summing the demand values of concurrent tasks. There were 3 single and 3 dual task combinations. Predictions were generated for the following four dependent variables: # retrievals, TOO detection rate, SF detection rate and SF detection time. These DVs were chosen because, unlike tracking error, they were valid measures across all 6 conditions, and unlike some of the other measures, there were substantial significant differences between conditions, a circumstance meaning that there were meaningful differences in performance to be predicted.

The correlations (N=6) between predicted and obtained data were 0.96 (# retrievals), 0.93 (TOO detection rate), 0.49 (SF detection rate) and 0.18 (SF detection time). In interpreting these results, it is not surprising that the data for the two SF task measures reflect a poor model fit. A single resource model obviously does not account for differences between auditory and visual display of information, differences which, as noted in section 3 above, accounted for large amounts of variance in SF detection performance. On the other hand, predictions of the single resource model across the other two aspects of task performance were remarkable good, accounting for over 85% of the variance of the data.

6.0 IMPRINT Modeling

Through the use of IMPRINT software, it is possible to simulate experimental data using three different task interference models: 1) VACP (visual-auditory-cognitive-psychomotor), 2) Goal-oriented, and 3) Advanced workload analysis. The latter of these analyses is based primarily on the Multiple Resource Theory, developed by Kantowitz and Knight (1976), Navon and Gopher (1979), and Wickens (1980, 1991). This is the analysis used in the current study.

The first step in building a simulation with the IMPRINT software is to define the mission. Figure R13 shows a sample screen where the modeler can choose a time standard, time

criterion, accuracy criterion, and mission criterion. This determines how often the mission must meet, and successfully complete without abort, the time standard. This is also where the modeler must choose which type of task interference theory to represent the data. In the current study, we chose a time, accuracy, and mission criterion of 90%.
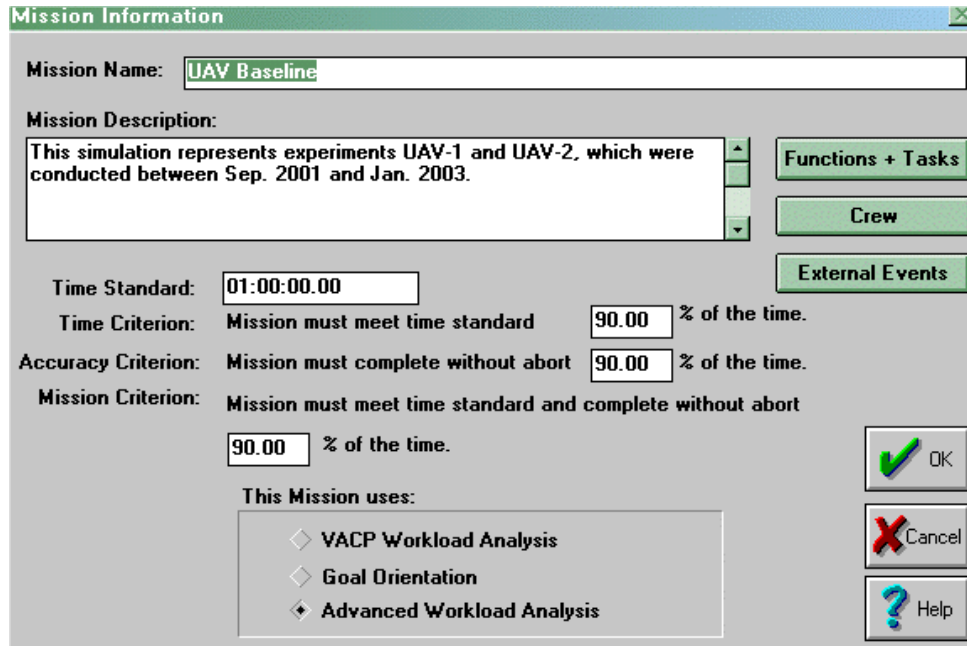

Figure R13. A splash screen of mission information.

The next step is to determine the functions and tasks. Examples of functions might be "initiate heading" or "target analysis". Tasks are more specific operations within each function. For example, when a pilot initiates heading, they might "check flight path coordinates", "set course", "adjust heading", "manipulate joystick", etc. Functions and tasks can either be defined in the screen labeled Figure R14, or later in the Network Diagram.
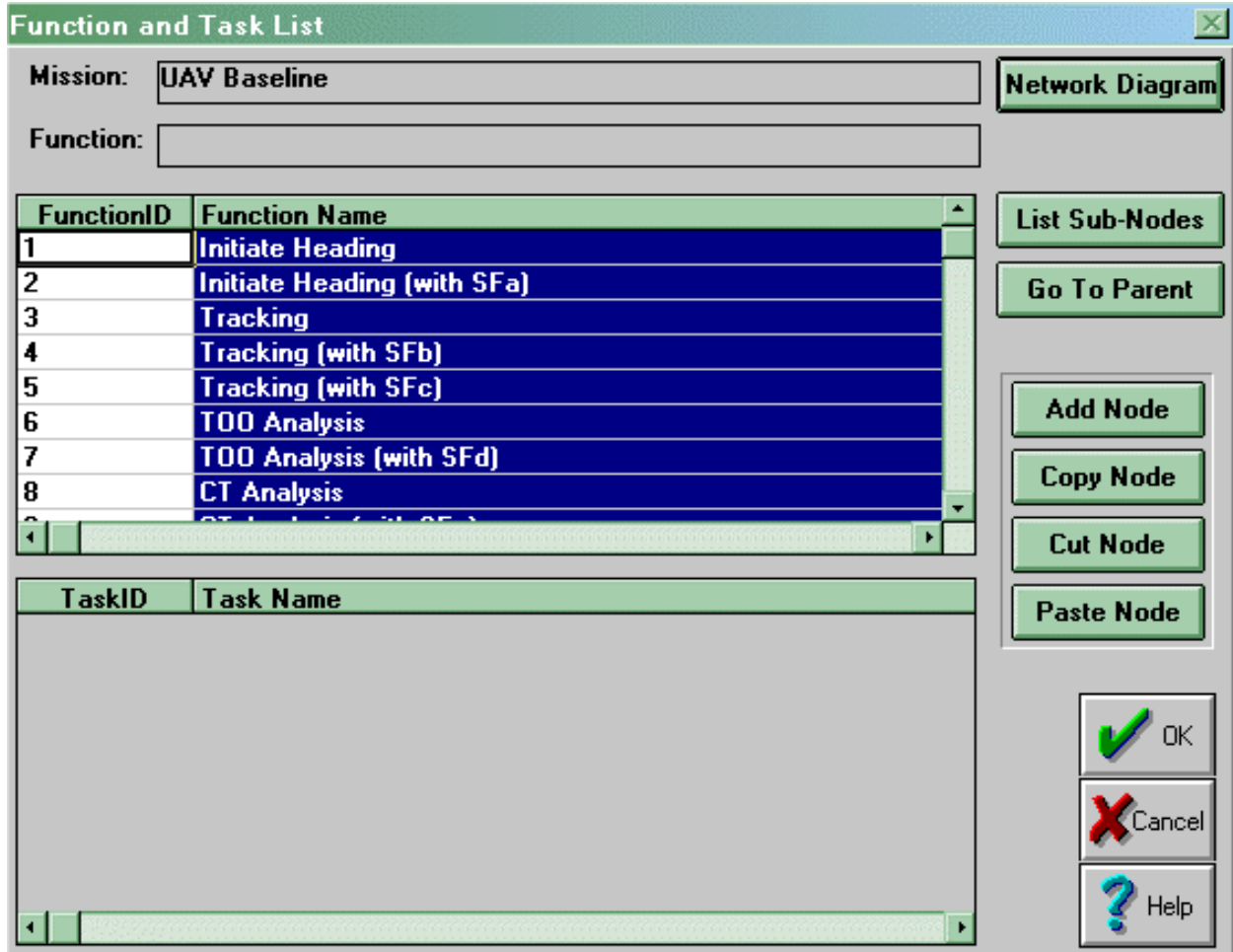
Figure R14. Function and Task list. Clicking on the "list sub-nodes" button will display tasks associated with each function.

In the current study, we defined 9 separate functions, with tasks listed below each function:

1. Initiate heading
    a. Set course
    b. Monitor SF
2. Initiate heading with SF_A
    a. Set course
    b. Correct SF_A
3. Tracking
    a. Continue course
    b. Search for targets
    c. Monitor SF gauges
4. Tracking (with recall)
    a. Continue course
    b. Search for targets
    c. Monitor SF gauges
    d. Recall coordinates and report question
5. Tracking (with SF_B)
    a. Continue course
    b. Search for TOO
    c. Correct SF_B
6. TOO analysis
    a. Analyze TOO
    b. Monitor SF gauges
7. TOO analysis with SF_D
    a. Analyze TOO
    b. Correct SF_D
8. CT analysis
    a. Analyze CT
    b. Monitor SF gauges
9. CT analysis with SF_E
    a. Analyze CT
    b. Correct SF_E

For purposes of simplicity, the current study did not attempt to parse the tasks into minute items of interest; rather, each task represents an assignment that may consist of many smaller sub-tasks. For example, one task might be to "search for targets". Theoretically, this could be broken down into smaller sub-tasks, such as "scan 3D display", "analyze terrain patterns", etc., but for our purposes, we chose to limit the model to tasks that had a clear purpose, with a beginning and an end.

Next, the modeler can open the Network Diagram and determine where to place each function and task. The network diagram, shown in Figure R15, also allows the modeler to determine specific information about each task.
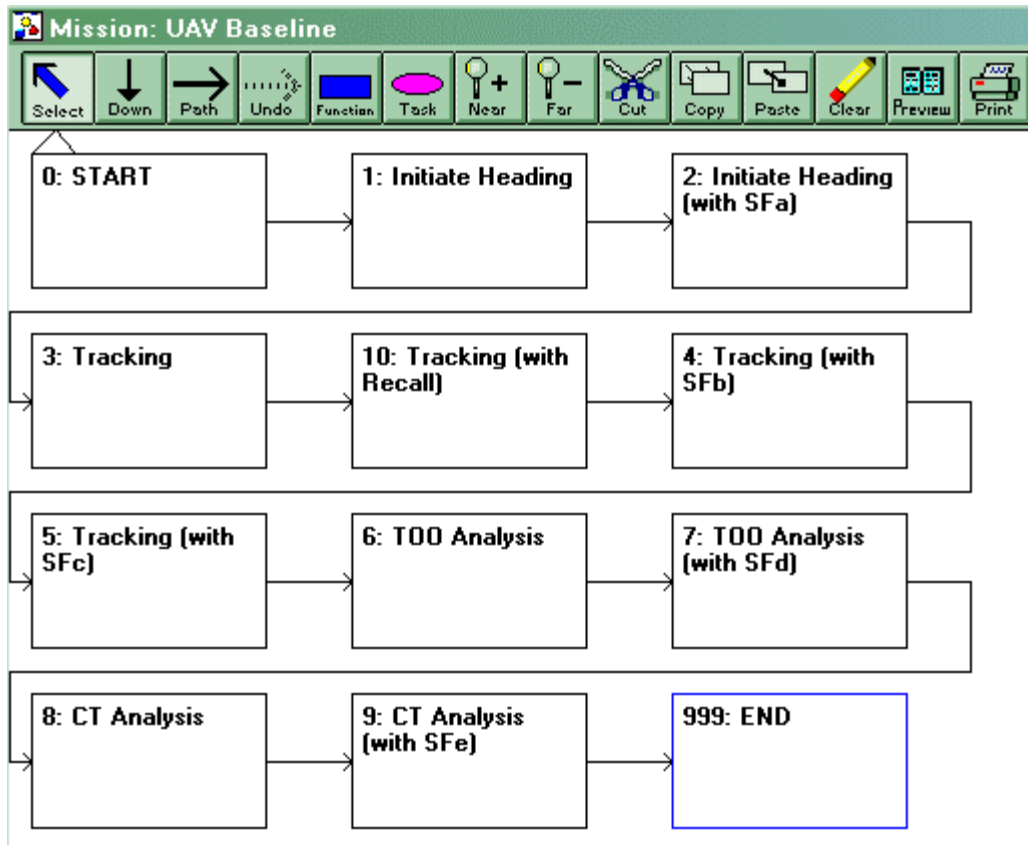
Figure R15. A sample network diagram showing mission functions.

If a modeler wants to add tasks to each function, then she can open that function and build a new diagram of tasks, which are affixed to that function. Figure R16 shows a sample task diagram. The modeler must state here the order of tasks and how they are to be performed temporally. If several tasks are to be completed simultaneously, as done with each function in the current study, then multiple paths go through each task and link back together again after completing all three tasks. The diamond with the 'M' in it, located just right of the START task, represents a multiple task branching logic, which we used as part of the Advanced Workload Analysis.
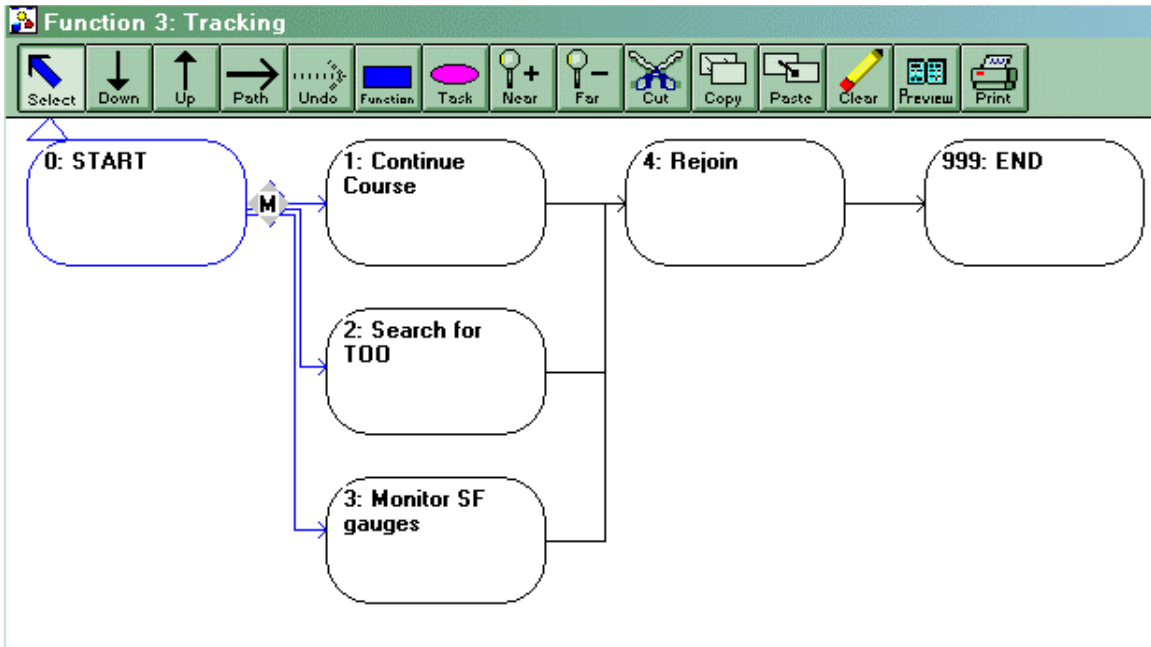
Figure R16. Task diagram. Clicking on a task opens a Task Information screen.

Figure R17. Task Information screen.

Figure R17 shows where many of the details regarding each task can be manipulated. Here is where the modeler determines the time and accuracy required of each task, the possible effects of multiple tasks, how to treat task failures, the workload measures associated with tasks (not used in the Advanced Workload model), crew assignment for each task, and additional taxons (not used in the Advanced Workload model). For our purposes, all accuracy and time standards were kept at 90%. This means that the operator had to complete the task in less than 1 minute at least 90% of the time, and he also had to complete the task accurately at least 90% of the time. The crew assignment was always the primary operator. When a task failed to complete due to time lapse, usually caused by resource overloads, the task was repeated until completed successfully.

The next step is to define the workload and crew member parameters, which involves several steps and is based on Multiple Resource Theory. First, the modeler must define the resources and interfaces. In the current study, the resources were visual, auditory, motor, speech, and cognitive resources. These were matched with the following interfaces: keypad, message box, 3D display, 2D top-down display, SF gauges, joystick, and the type of response pilots used. Table R2 shows how we paired the resources to the interfaces. An "X" represents a combination between a particular resource and the interface it is aligned with.

Table R2. Paired resources and interfaces.

	Visual	Auditory	Cognitive	Motor	Speech
Keypad	x			x	
MessageBox	x	X (Auditory condition only)	x		
3D Display	x		x		
2D Display	x		x		
SF gauges	x	X (Auditory condition only)	x		
Joystick	x			X	
Verbal Response					x

After defining the resource/interface (R/I) combinations, the modeler must assign R/I combinations to each mission task. For example, in the current study, the task "set course", involved the following R/I combinations: Visual-MessageBox, Visual-2DTopDown, Motor-Joystick, Cognitive-MessageBox, and Cognitive-2DTopDown.

Next, the modeler assigns task demand values to each task. These task demands values can either be chosen from a list provided by IMPRINT, which is based primarily on previous literature that quantifies the difficulty of particular tasks, or they can be added arbitrarily by the modeler. In our simulation, we always accepted IMPRINT's suggestions unless there was no clear match between the suggestion list and the actual task we modeled. In those cases, we interpolated the value by using the two closest values on the list.

Lastly, the modeler assigns the channel conflict values, based on the conflict matrix developed from Multiple Resource Theory.

6.1 IMPRINT results

It should be noted that the parameters used in the IMPRINT modeling were based on Wickens (2002) recommended values, and were not adjusted post hoc. Figure R18 presents the predicted interference values generated by IMPRINT for the three conditions across each of the 9 dual-task situations.
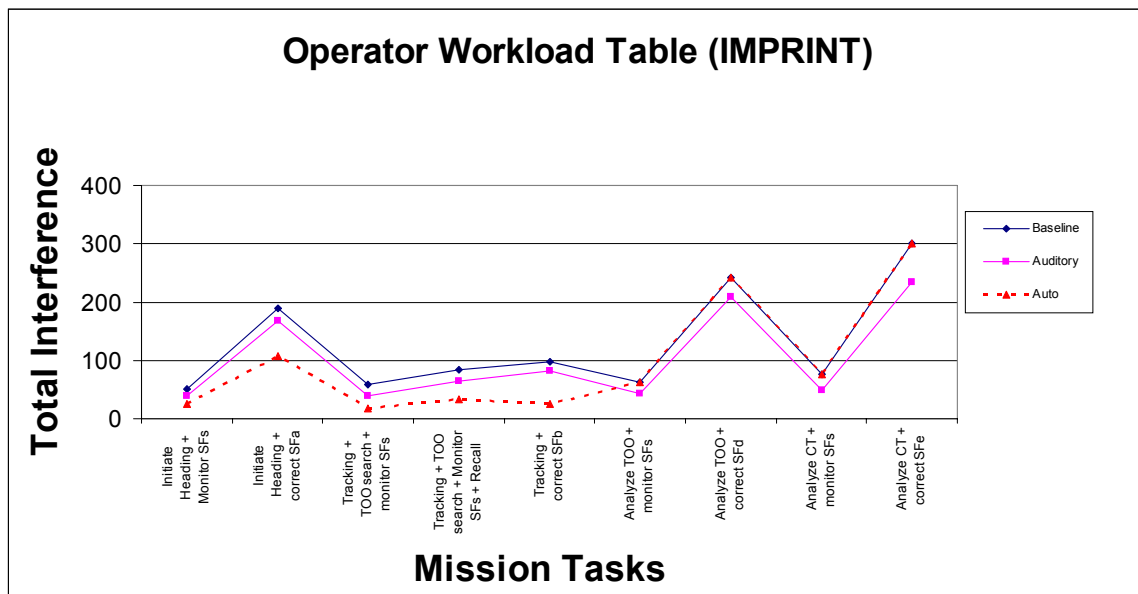

Figure R18. Interference values for dual-task combinations.

The results from Figure R18 clearly show strong MRT predictions of improved dual-task performance in the auditory condition over the baseline condition for monitoring / correcting SFs and recalling flight instructions, based on reduced interference between these task combinations. As seen in the graph, interference levels were lower for all 9 task combinations in the auditory condition. This correlates well with the actual performance data, which show improved SF detection rates (tasks 1, 3, 6, and 8 in the IMPRINT analysis) and detection times (tasks 2, 5, 7, and 9), as well as improved recall of the flight instructions (task 4) in the auditory condition. Furthermore, the level of improvement also seems to be fairly well predicted in the IMPRINT simulation; that is, the interference values generated by IMPRINT are 10-25% lower in the

auditory condition, which appears similar to the degree of improvement in most of the performance data.

One noticeable difference is in SF detection times, which were more than twice as fast in the auditory condition, despite only a 10% reduction in interference values. This may be due to the nature of the task; detection time of a SF is simply a reaction time task, and a slight reduction in dual-task interference may be all that is necessary to drop below the threshold of cognitive tunneling on another task. Once the mental workload has dropped below this arbitrary threshold, then parallel processing is feasible, and the pilot is able to respond instantly to the SF rather than wait until the side task is finished (i.e., serial processing).

With regards to TOO detection, the IMPRINT results appear to predict improved performance in the auditory condition, but failure to see these results in the performance data is probably due to pilot choice. Pilots were free to allocate extra resources, freed up by auditory offload of one task, to either of the two tasks in a dual-task situation. It is apparent from the data that they chose to allocate these resources to the SF task and not to the concurrent TOO task. One weakness in IMPRINT modeling is that it cannot predict where the operator will allocate these resources.

In the automation condition, IMPRINT correctly predicted improved tracking and detection rates for some SFs (i.e., SF_A and SF_B), but incorrectly predicted faster detection times to these SFs. Theoretically, it seems logical that pilots should have been able to response more quickly to SFs since they had extra resources available, but the data do not show this. As mentioned earlier, one explanation may be that the tracking task in the baseline condition was so easy the difficulty level between the two conditions was too similar to facilitate improved performance in the automation condition. A post hoc adjustment of IMPRINT task demand values would probably correct this discrepancy.

The IMPRINT simulation did an exceptional job of predicting TOO detection rates in the automation condition. Because of the reduced task interference between tracking and target search, pilots were indeed able to detect almost twice as many TOOs in the automation condition than in the baseline condition. This corresponds with the 50% reduction in task interference, although it should be noted that levels of task interference are not necessarily expected to correlate serially with levels of actual performance.

In summary, IMPRINT appears to generate simulation results that juxtapose quite nicely with experimental data in the UAV environment. The foundation of the IMPRINT model used in the current study is based on MRT, and helps to validate that theory's model of task interference, particularly when the operator divides tasks between two different modalities.

Discussion

Single task effects

The general pattern of results from the single task conditions of the present experiment appear to generally replicate the findings of the previous experiment (Wickens & Dixon, 2002). Thus, the automation offload generally improved TOO monitoring and SF detection, while the auditory offload assisted SF detection, but not the TOO monitoring task. As before, there appeared to be a large degree of interference in the baseline condition between monitoring the flight path, the TOO display, and the SF display, particularly in the added cognitive/motor requirements of "dealing with" command targets, targets of opportunity, or system failures (i.e., image inspection and report). One important contrast of the current results with those of the previous experiment is that here we found that the auditory offload did help SF detection, even when those system failures occurred during the cognitively demanding phases of TOO and command target image inspection. Thus in this experiment, unlike the previous one, the severe case of "cognitive tunneling" was not observed, a difference we attribute to the added incentives that were provided for good performance. In the following discussion, we now turn to the joint effects of **task load** (one versus two workstations) and the two different offloads.

Task loading effects

The dual-UAV requirements imposed a fairly consistent decrement across most aspects of performance except the primary tasks of tracking (flight trajectory control) and image reporting accuracy. This "protection" of these primary task measures can be readily interpreted, given both its importance for the mission, and the fact that the flight control task itself was of sufficiently low bandwidth that pilots could readily divert attention from monitoring its track on one UAV to reallocate to other tasks in the other, without producing a deviation in performance. In contrast, both of the tasks that might be viewed as "secondary" (TOO monitoring, SF monitoring), as well as the report retrieval (memory) task, all showed some indications of a cost when the UAV supervision requirement was doubled. These costs were mitigated by the two different offloads in different ways, as we describe below.

Auditory offload. The auditory offload had no observable benefit on tracking or TOO monitoring. We assume that the short "check glances" to the SF display, which were needed in the two visual conditions (baseline and automation), but avoided in the auditory condition, were of sufficiently short duration that the elimination of these short time spent away from the other tasks could not be used to improve their performance. This is in the same way that a good driver can make short glances downward to the instrument panel without sacrificing performance on a low bandwidth driving task (Horrey & Wickens, 2002). Associated with the primary task of mission goals, there was an auditory offload "benefit" to the CT information retrieval task, in that providing this information auditorially reduced the frequency with which such repeats were required. We assume that in the two visual conditions, pilots who were engaged in the tasks of tracking, TOO monitoring, and system monitoring, were often required to divert their gaze from the instruction box to monitor these channels, thereby degrading the quality of comprehension of this instructional material and forcing it to be re-read. Such diversion did not need to occur when the instructions were presented auditorially, given the availability of separate perceptual (visual versus auditory) resources.

Most notably, the auditory offload had a dramatic benefit for the SF task, to which the auditory offload was directly attached, as shown in Figure R8. The offload appeared to "buffer" this task, not only from the effects of dual-UAV loading, but also from the effects of cognitive tunneling, which had been previously observed by Wickens and Dixon (2002) during the target examination phase, for both the TOOs and the CTs. It is important to emphasize that, while there was a gain in performance for the SF task by its auditory delivery, such delivery did not impose any cost on the ongoing visual tasks, an effect that has sometimes been observed as a sort of "pre-emption" imposed by auditory onsets (Helleberg & Wickens, in press).

Automation Offload. In contrast to the auditory benefit, primarily localized to the SF task, the benefits of automation were generally more widespread, an effect not altogether surprising because automation entirely eliminates a task (monitoring and correcting flight path trajectory), whereas auditory offload only altered the delivery of task-relevant information. Naturally, the benefit of automation to tracking performance was an intentional artifact, as is the case with most autopilot studies (that is, the autopilot tracker is designed to produce nearly perfect performance). In contrast to the auditory offload, automation showed a substantial benefit to the perceptually challenging TOO monitoring task, a benefit that was only partially attributed to the more accurate flight paths flown by the autopilot. That is, not having to monitor the tracking navigation display freed up visual resources to inspect the TOO image display more closely, and these released resources were even more advantageous in dual-UAV than in single-UAV conditions. That is, the automation benefit to the detection of targets that did pass through the TOO image display was both larger in percentage, and more significant statistically, in dual- than in single-task conditions. Furthermore, in dual-, but not single-task conditions, this benefit was reflected in the slightly shortened the time required to zoom in and report a TOO identity.

The automation offload also assisted performance on SF monitoring, improving its detection accuracy equally in both single- and dual-UAV conditions, although it had no benefit on SF detection time. It should be noted here that in both the automation and the baseline conditions, the need to monitor a second UAV slowed the SF response time by about 3 seconds (see Figure R7). One way of interpreting this value is that it reflects the frequency with which attention is switched between the two UAV workstations, at approximately 3-second intervals. We revisit this issue below, in considering the relevance of single channel theory.

Theoretical Interpretations and relevance for workload models.

The current data provide evidence for some single channel aspects of behavior, particularly within a single-UAV. We assume, given the high acuity demands of the TOOs, that pilots simply could not monitor this display for their appearance when their visual attention was occupied elsewhere, either within the same workstation, or on the other workstation. Also, as noted above, we assume that the 3-second dual task cost to visual SF detection described above probably reflected the inability to see a SF on one UAV, when vision was occupied with the other. Furthermore, the direct timeline analysis of overlapping events on the two workstations, presented in Figures R9-R11, indicates that the total time to do certain pairs of tasks appearing in the two workstations concurrently exceeds the sum of the time that would be predicted for each task alone. The fact that the actual time **exceeds** the time predicted even by a single channel model, suggests that there is an added switching penalty for going between the two tasks (Miller, 2002).

However it is also important to note that these strict single channel theory predictions were mitigated in two respects. First, the automation condition, and in particular, the auditory condition, reduced the magnitude of single channel behavior. Indeed, in the auditory condition, the Figures R9-R11 actually indicate positive evidence for concurrent processing, consistent with a multiple resource account. In the automation condition, this reduction in the apparent magnitude of single channel behavior is consistent with the findings of Liao and Moray (1993), that when the number of tasks is reduced, more evidence arises for parallel processing.

The second mitigation of strict single channel processing predictions was evident from Figure R12, in which it can be seen that the predictions of a linearly increasing delay in processing of the second arriving task as its arrival time is earlier, are clearly **not** confirmed. In contrast to the findings of Kerstholt et al. (1996), or Moray and Rotenberg (1986), operators in the current domain were apparently <u>not</u> postponing action on the second arriving task until the first was completed, a behavior that, if observed, would have reflected strict single channel processing. As described above, there is evidence that pilots may be sampling each display at approximately 3-second intervals (on the average). Presumably, faced with the concurrent processing demands of "examination tasks" on each workstation, pilots alternated processing of each in such a way that both tasks bore the brunt of their concurrency. Indeed, this added delay with reduced arrival interval might be shown in the **first** arriving task, although such data are not yet analyzed. It is also consistent with the switching cost data in Figures R9-R11 that showed pilots switching between tasks with some frequency, given that the cost of a switch in task activity can be substantial (Miller, 2002).

Some aspects of single resource theory were also in evidence. We have already noted the consistency of the current data with the "effort-mobilizes more resources" conception put forth by Kaheman (1973), in noting the elimination of single channel cognitive tunneling for the auditory condition. Here the contrast with the previous experiment is important. The added incentives for excellent performance in the current experiment, absent in the previous, presumably caused pilots to invest more effort into the task, thereby mobilizing more resources, and mitigating dual task decrements in the auditory condition where there was no peripheral bottleneck We also find that, with some exceptions, decrements in dual task conditions are not substantially greater than in single task conditions. This can be ascertained by comparing the decrements in performance from the baseline to either of the offloads, or from the "easier" SF type (SF$_B$) to the more challenging type (SF$_D$ and SF$_E$), between single and dual task conditions. Single channel theory would typically predict a doubling of those decrements ("massive interference"), something not found here. The reduced, but still present decrements, are consistent with resource theory.

The extent to which **single** resource theory can adequately account for the data can be best evaluated by correlating the decrement values with the sum of task demand values, as shown in Table 2. To the extent that such correlations are high, it suggests that most variance in workload (here related to task overload performance costs) can be accounted for simply by variance in how difficult the tasks are rated to be. As our analysis showed, correlations of model fits for some of the performance measures, TOO detection rate and # of CT repeats were quite high, with the single resource demand model accounting for over 85% of the variance in performance across the six conditions. At the same time, the single resource model fit was less impressive in accounting for variance in SF monitoring performance. This is not surprising,

given the strong roll of **multiple** resources in influencing performance on the SF task, as discussed above. We should note however that there are other ways of making single resource model predictions. On the one hand, we could have used pilots rating of task difficulty as our inputs to the demand vector, rather than our own analyst ratings. On the other hand, we could have made more refined predictions by predicting different epochs of performance of a given task, whose resource demands might change (e.g., making separate predictions for different system failure types). This remains to be done.

In conclusion, it does appear that different aspects of all three models, account for some parts of the data. Single channel theory accounts nicely for the task switching effects observed. However single channel theory cannot really handle aspects of differential task difficulty, except when those differences translate directly into task time. However in the case of tasks like SF monitoring or tracking monitoring, these really do not lend them selves to time measures, since they are continuous ongoing tasks. Hence there is value added in considering task demands; and as we saw, such considerations were very useful in accounting for variance in some, but not all tasks. Finally, it appears that multiple resource theory is responsible for accounting for some substantial aspects of time sharing performance that were not accounted for by models based on the other two theories, particularly the difference between auditory and visual delivery. An effective computational model therefore needs to incorporate all three characteristics: resource demand (SRT) and resource structure (MRT), along with some single channel switching assumptions, that characterize how task are prioritized in sequence, when demand or structure are such that concurrent task performance is impossible.

With regard to the fundamental issue addressed by this study, is single operator control of two UAV's feasible? The answer is only a very qualified "yes". The basic mission requirements were met with two, as well as one UAV. However, even with the various offloads, dual UAV requirements sacrificed some aspects of vital secondary task performance and in particular, monitoring for targets of opportunity. And these findings were observed in "best case" circumstances in which automation was essentially perfect. Following the review of Wickens and Xu (2002), we anticipate substantial problems in dual UAV control with imperfect automation.

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