THE INTERNATIONAL JOURNAL OF AVIATION PSYCHOLOGY, 6(4), 307–320

FORMAL PAPERS

Studies of Cockpit Task Management Errors

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Cockpit task management (CTM) is the management level activity pilots perform as they initiate, monitor, prioritize, and terminate cockpit tasks. To better understand the nature and significance of this process, we conducted 3 empirical studies: a review of National Transportation Safety Board aircraft accident reports, a review of Aviation Safety Reporting System aircraft incident reports, and a simulator experiment. In the accident report study, we determined that CTM errors occurred in 76 (23%) of the 324 accidents we reviewed. We found CTM errors in 231 (49%) of the 470 incident reports we reviewed. In the simulator study, we found that CTM performance was inversely related to workload. We conclude that CTM is significant to flight safety and recommend that this realization be reflected in pilot training, in cockpit procedures, and in research to develop pilot aiding systems.

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Flight crews not only have to perform individual tasks to accomplish missions; they must manage tasks as well. They must make sure that tasks are started and stopped at the right times and that undue attention to lower priority tasks does not prevent the correct and timely completion of higher priority tasks. Just as failure to perform tasks correctly can lead to accidents, failure to manage tasks correctly can have catastrophic consequences as well.

This article describes three related studies that have helped us to understand the nature and significance of task management in commercial flight operations: a study of aircraft accidents, a study of aircraft incidents, and a study of task management behavior in the laboratory.

BACKGROUND

We define a *task* as a process performed (at least partly by a human) to achieve a goal, such as to fly to a waypoint, descend to a desired altitude, obtain a clearance from air traffic control, or restart an engine. Most human factors and engineering psychology researchers have focused on the task as the unit of human behavior, and many theories of task performance and errors have emerged.

A less prominent line of research has addressed the higher level activity of managing multiple, concurrent tasks. For example, Johannsen and Rouse (1979) introduced the notion of a time-sharing computer system as a metaphor for human multiple task performance but did not address in any detail the nature of the executive task, that task responsible for managing other tasks. In her studies of workload, Hart (1989) found that participants attempted to maintain a relatively constant level of workload by means of a form of task management: shedding or assuming tasks as workload increased or decreased. Moray and his colleagues (1991) proposed scheduling theory as a normative model for how operators manage multiple tasks and found that unaided human participants adopted suboptimal scheduling strategies. In a simulator study, Raby and Wickens (1994) investigated the effect of workload on task management, finding that as workload increased, participants adjusted task performance strategies.

Our research is based on a theory developed by Funk (1991) to describe task management behavior in the cockpit domain. According to this theory, cockpit task management (CTM) consists of the following functions:

1. *Task initiation*: The initiation of tasks when appropriate conditions exist.
2. *Task monitoring*: The assessment of task progress and status.
3. *Task prioritization*: The assignment of priorities to tasks relative to their importance and urgency for the safe completion of the mission.
4. *Resource allocation*: The assignment of human and machine resources to tasks so that they may be completed.

5. *Task interruption*: The temporary suspension of lower priority tasks so that resources may be allocated to higher priority tasks.
6. *Task resumption*: The resumption of interrupted tasks when priorities change or resources become available.
7. *Task termination*: The termination of tasks that have been completed, that cannot be completed, or that are no longer relevant.

Objectives

The broad purpose of our research was to determine the nature and significance of CTM in flight operations and, if appropriate, make recommendations to improve it. To achieve this, the following specific objectives were formulated:

1. Develop a taxonomy of CTM errors.
2. Study CTM behavior in operational settings by means of accident and incident reports.
3. Study CTM behavior under controlled laboratory conditions.
4. Make recommendations to improve CTM behavior through training and design.

The organization of this article follows that of the objectives.

CTM Error Classification

Chou and Funk (1990) developed an initial CTM error taxonomy consisting of seven general CTM error categories corresponding to the aforementioned seven functions of CTM. Each category was further described in terms of specific error classes. Use of the initial taxonomy in preliminary analyses of accident and incident reports showed some of the error classes to be redundant and the taxonomy, as a whole, to be difficult to apply consistently.

As a result, we revised the taxonomy to include the CTM error categories shown in Table 1. To summarize, a task may be initiated or terminated too early, too late, under incorrect conditions, or for incorrect reasons; or it may not be initiated or terminated at all. Furthermore, a task may be given too high or too low a priority. This revised taxonomy served as the basis for our accident and incident studies, descriptions of which follow.

CTM Errors in Aircraft Accidents

The underlying causes of aircraft accidents usually fall into the three broad categories of mechanical factors, weather, and pilot error. However, these labels

TABLE 1
CTM Error Taxonomy

Error Categories	*Possible Classifications*
Task initiation	Early
	Late
	Incorrect
	Lacking
Task prioritization	Incorrect
Task termination	Early
	Late
	Incorrect
	Lacking

should not be used to mark the end of further analyses for human and other system performance errors because aircraft accidents are usually the outcomes of a number of contributing factors. In an effort to determine whether some instances of pilot error could be explained in terms of CTM, and thereby begin to understand the significance of CTM to flight safety, we reviewed a set of aircraft accident reports (Chou, 1991).

Our analysis reflects the examination of the abstracts of 324 National Transportation Safety Board (NTSB) aircraft accident reports concerning accidents occurring between 1960 and 1989. After reviewing the 324 National Technical Information Service abstracts of these reports, we removed accidents that were obviously unrelated to this study from the screening process. For example, accidents due primarily to weather and mechanical failures were removed. This elimination process left 76 accident reports for further analysis.

Following the initial screening, we selected a representative set of cases for further study, based on the following considerations. First, we chose the cases so as to include a complete set of CTM errors as listed in Table 1. Second, we chose cases involving conditions we believed we could reconstruct in a simulated environment. Based on these considerations, we settled on a set of cases including the following accidents: Eastern Flight 401, a Lockheed L1011 (NTSB, 1973); China Airlines Flight 006, a Boeing 747 (NTSB, 1986a); Piedmont Flight 467, a Boeing 737 (NTSB, 1986b); Air Florida Flight 90, a Boeing 737 (NTSB, 1982); Comair Flight 444, a PA31–310 (NTSB, 1979); and a Texasgulf Aviation flight, a Lockheed JetStar (NTSB, 1981). For each accident in this set, we carefully studied the data and conclusions of the NTSB investigators and constructed an operational task context.

Each context was a graphical representation of cockpit activities during the time leading up to the accident. It included the number and type of concurrent tasks competing for the flight crew's resources, the state of each task (pending, active, interrupted, or terminated), and selected system state variables (e.g., aircraft altitude, speed, etc.).

For example, Figure 1 shows the task context for Eastern Flight 401, a Lockheed L1011, in the last 10 min before the accident. In this accident, the flight crew became preoccupied with a possible landing gear indicator fault and failed to notice the aircraft's gradual descent, which eventually led to the crash. The upper portion of this figure shows crew activity on four concurrent tasks in this period: aircraft control (FLYING), ATC communication (COMM), diagnosis of the landing gear indicator (DIAGNS), and inspection of crew-accessible parts of the landing gear itself (INSPCT). The lower portion of the figure shows aircraft altitude and time. This figure shows our finding that the flight crew's attention was focused on the landing gear problem to the exclusion of the flight control task.

We identified this as a CTM error and classified it as a task-prioritization-incorrect error, backing up our interpretation of the data with the conclusions of the NTSB. With the insights gained from this detailed analysis and using the data and conclusions in the accident abstracts and full reports, we identified and classified 80 CTM errors in 76 of the 324 accident reports. That is, we found that CTM errors occurred in about 23% of the accidents reviewed. These errors, summarized by category, are presented in Table 2.

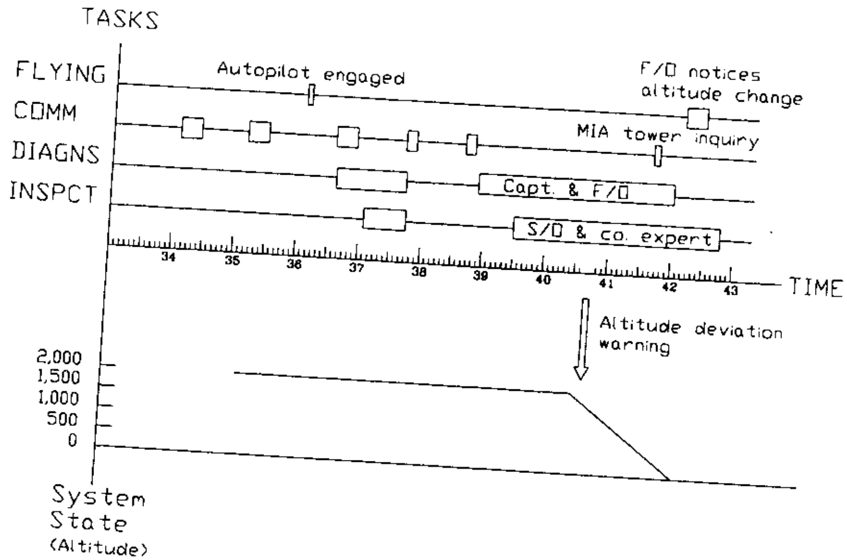

FIGURE 1 Task context for Eastern Flight 401.

TABLE 2
CTM Errors Identified and Classified in 76 (23%) of 324 NTSB Accident Reports

CTM Error	*Number of Accidents*	*Percentage of CTM Accidents*	*Number of CTM Errors*	*Percentage of All CTM Errors*
Task initiation	35	46	35	44
Task prioritization	24	32	24	30
Task termination	21	28	21	26

Note. CTM = cockpit task management; NTSB = National Transportation Safety Board. Total number of CTM errors = 80.

Although we cannot state categorically that CTM errors were the sole or even primary causes of these accidents, we do believe that they played significant roles. Had the errors been prevented, the accidents probably would not have occurred. We conclude that the moderately high incidence of CTM errors in the accidents—76 (23%) of 324 accidents—is supportive evidence that CTM is a significant factor in flight safety.

CTM Errors in Critical In-Flight Incidents

Fortunately, aircraft accidents are very rare events. Unfortunately, a set of accidents such as the one we studied might be a very biased sample of the operating environment. Therefore, inferences made from a set of accidents may have little relevance to reducing the likelihood of future accidents. For that reason, we next turned our attention to aircraft incidents (Madhavan, 1993). An incident is defined as "an occurrence other than an accident, associated with the operation of an aircraft, which affects or could affect the safety of operations" (Federal Aviation Regulations, 1994). Although incidents by definition do not involve death, serious injury, or substantial aircraft damage, it is clear in retrospect that most airline accidents were foreshadowed by clear evidence that the problems existed long before as incidents. Our specific objective in analyzing aircraft incidents was to determine the significance of CTM in flight operations more representative of normal conditions.

We used as a source of aircraft incident information NASA's Aviation Safety Reporting System (ASRS). The ASRS database consists of anonymous reports filed by pilots and air traffic controllers describing events in which accidents nearly occurred or in which flight safety was seriously compromised.

Our preliminary analysis of CTM errors focused on aircraft incident reports relating to in-flight engine emergencies (99 reports) and controlled flight toward terrain (CFTT; 205 reports). We found CTM errors in 19% and 54%, of these reports, respectively. The high incidence of CTM errors in the CFTT reports, as well as the fact that over 49% of all airline accidents occur during approach and landing (Boeing Commercial Airplane Group, 1994, March), caused us to focus further attention on the terminal phases of flight. At our request the ASRS office furnished us with 243 additional reports pertaining to these phases.

As in most ASRS studies, we used the narrative section of the reports for our analysis. The narrative is the section of the report in which the reporter states in his or her own words what happened and why it happened.

In the narratives, we focused on activities directly related to task management only. Incidents involving crew personality differences and other sociological factors were excluded. When narratives were unclear about the specific errors committed (i.e., no categoric admission of the errors by the reporters), some inferences were made about the errors based on our knowledge of standard operating procedures as gleaned from aircraft operations manuals, accident reports, incident reports, and other aviation literature (e.g., Stewart, 1992). Key words and phrases in the narratives—such as "forgot," "omitted," "memory lapse," "oversight," etc.—enabled us to home in quickly on the error classification. As an illustration of our method, one such report (typical of the reports in this flight phase), is reproduced, in part, here (ASRS Rep. No. 144766). This excerpt is verbatim from the ASRS database except that case has been converted (ASRS reports are recorded in all uppercase letters). CTM error classifications are inserted in square brackets and are explained following the excerpt:

> Capt. was flying acft. A tornado watch had him worried and asked F/E to contact FSS to get details descending into DTW [task prioritization incorrect]. His radio interfered with COM on radio #2 which I was on with APCH. During this confusion dsnt and apch clrncs had to be repeated a few times distracting my x-chk of cpt's INS. Intercepting LOC capt went right through the LOC and saw he had 66 degs not 33, as apch calls for. I called out that and he put 33 in the window, corrected back and overshot again (APCH asked if we needed vectors back for a new apch). He said no. I said "I don't like the look of this." We had full LOC deflection and were above G/S. Capt. said "let's see how it is at 1000." At 1000' he did manage to get back on LOC and kept descending to a successful lndg [task termination lack]. Capt. had poor CRM and poor judgement. I should have said,"go missed apch," F/E should have said the same, but was still doing chklist—late [task initiation late] because of talking to FSS. It was the first time I had seen an apch so messed up! I will never allow it to happen again![1]

[1]Capt., cpt = captain; F/E = flight engineer; FSS = flight service station; APCH = approach control; apch = approach; dsnt = descent; clrncs = clearances; x-check = cross-check; INS = inertial navigation system; LOC = localizer; G/S = glide slope; lndg = landing; CRM = crew resource management; chklist = checklist.

The captain elected to perform a lower priority task (radio for weather update) at a critical point in the flight (final approach to land), which caused the F/E to delay his checklist. The reporter implied that the captain should have aborted the landing. From the narrative it appears that the captain's attention was allocated primarily to the tornado watch with little left for landing safely (as evidenced by his mis-setting the localizer course and continuing with the landing despite being at full localizer deflection).

From the 540 ASRS incident reports we obtained, we eliminated duplicates. We then applied the CTM error taxonomy to the remaining 470 unique reports. We found CTM errors in 231 (49%) of the 470 ASRS incident reports. The results of the analysis are presented in Table 3.

Task initiation appears to be the most significant CTM error category, accounting for 42% of the CTM errors identified. Task initiation errors included early descents, late configurations, and failures to tune navigation and communication radios. Task prioritization errors accounted for 35% of the CTM errors and included distractions by weather and traffic watches. The remaining 23% of the CTM errors were in the task termination category. These included early autopilot disengagements, altitude overshoots, and improperly continued landings under unsafe conditions.

Although task initiation appears to be the largest CTM error category, that may be somewhat misleading. The failure to start a task on time (or at all) or the decision to start a task too early may often be explained as misprioritization. That is, excessive priority placed on one task may delay the start of a second task or cause the flight crew to start the first task before they should. Similar arguments can be made for task prioritization versus task termination. Although the initiation and termination categories are useful for understanding errors, their causes, and their consequences, task prioritization should perhaps draw our greatest attention for the development of countermeasures. We conclude that the high incidence of CTM errors in the incident reports—231 (49%) of 470 reports—is supportive evidence that CTM is a significant factor in flight safety.

TABLE 3
CTM Errors Identified and Classified in 231 (49%) of 470 ASRS Incident Reports

CTM Error	*Number of Incidents*	*Percentage of CTM Incidents*	*Number of CTM Errors*	*Percentage of All CTM Errors*
Task initiation	137	59	145	42
Task prioritization	133	58	122	35
Task termination	83	36	82	23

Note. CTM = cockpit task management; ASRS = Aviation Safety Reporting System. Total number of CTM errors = 349.

FLIGHT SIMULATOR STUDY

From our accident and incident studies, we determined that CTM is significant enough to warrant further study. However, we felt that a different approach was needed to better understand the nature of CTM behavior. Aircraft accidents are rare events, thus providing few opportunities for developing insights into error processes, which are, in any case, very difficult to reconstruct. By the same token, though ASRS incident reports can provide firsthand information on abnormal cockpit operations, they are subject to self-reporting biases and other problems. Therefore, controlled experimentation provides a useful alternative, serving to compensate for the drawbacks noted previously and to provide an opportunity for objective observations. An additional advantage of the simulation method is that it enables observation of how human operators manage tasks under normal conditions.

The main objectives of our experiment were to elicit and observe CTM errors similar to those identified in the accident and incident analyses and to identify the factors leading to such errors. Our approach was to have participant pilots fly a low-fidelity flight simulator in several flight scenarios and observe and analyze their behavior in managing and performing concurrent flight tasks.

Apparatus

Our flight simulator consisted of three networked personal computers. The system simulated a generic, two-engine commercial transport aircraft. One computer simulated aircraft dynamics using a very simple aerodynamic model and produced a simple primary flight display showing heading, altitude, airspeed, pitch, and roll. The participant controlled the simulated aircraft by means of a joystick. A second computer simulated the navigation system and presented a moving map display. The participant could use the navigation display for planning and navigating purposes and could control map scale and orientation (north up or track up) by means of mouse-activated controls. The third computer simulated aircraft subsystems, including engines and the hydraulic system, and generated a simplified engine indication and crew alerting system display. Aircraft subsystem models included failure modes that could be triggered by script files and that required participant interaction by mouse-activated controls to correct.

Participants

Twenty-four unpaid participants from Oregon State University participated in the experiment. The participants included 2 engineering faculty members, 3 undergraduate engineering students, and 19 engineering graduate students. Two of the participants had private pilot licenses with 120 to 150 hr of flight time. The other participants had no flight experience. Sixteen participants participated in two pilot studies, and the remaining 8 participants took part in the data collection runs. The pilot studies were used for refining training procedures and flight scenarios.

Procedures

Participants received a 60-min training session prior to each experiment. This session included viewing a training videotape and running a simplified scenario. The scenarios were categorized into six different levels by the following independent variables: resource requirements, maximum number of concurrent tasks, and flight path complexity. Following concepts from multiple resource theory (Wickens, 1992) and workload index (W/INDEX; North & Riley, 1989), scenarios were created and rated according to the requirements for visual resources (to acquire needed information from simulated visual displays), manual resources (to manipulate simulated controls), and mental resources (to recognize, remember, calculate, and decide). Each scenario received an aggregate resource requirements rating (low or high). The number of concurrent tasks was defined as the maximum number of tasks requiring participant attention at any point in the scenario (three or six). Flight path complexity (easy or hard) was varied by adjusting the sharpness of turns at waypoints in the flight path.

A split-plot design (Steel & Torrie, 1980) was used for the experiment. The latter factors (number of concurrent tasks and flight path complexity) were crossed to provide four levels for whole unit factors. These four whole unit factors were then crossed with the subunit levels (resource requirements) to provide eight treatments. Given this design, eight participants were used to provide two responses for each treatment. Each participant performed two levels of the subunit factor (low and high resource requirements), and the assignment of treatments to participants was randomized to control learning effect. That is, four participants started with the high resource requirements treatment and then performed the low resource requirement treatment, whereas the other four participants performed their treatments in the reverse order.

Performance Measurement

The following performance measures were used:

1. Average response time to system faults.
2. Root-mean-square (RMS) flight path error.
3. Task prioritization score.
4. Number of tasks that were initiated late.

The response time to a system fault was defined as the time from the occurrence of the fault (such as an electrical bus fault) until a compensating response was initiated. This corresponded to task initiation. The task prioritization score was determined from paired comparisons between tasks and was used for measuring task prioritization performance. A score of +1 was assigned when a correct prioritization was made by the participant (i.e., attention was first given to the higher priority task); otherwise a −1 was assigned. Scores for the remaining tasks were set to zero. Finally, a task was said to be initiated late if the participant did not respond to the task 60 sec after it had been activated. This was used to measure task initiation performance.

Results

The analysis of variance (ANOVA) results for factors with significant effects are summarized in Table 4. We found that the resource requirements level had a significant effect on the average task response time. That is, higher resource requirements increased delays in initiating a task. However, neither combination of flight path complexity nor maximum number of concurrent tasks (alone or in combination) had a significant effect on task response time.

During the experiments, participants were warned if 60 sec passed after the occurrence of a system fault and no actions were taken. Thus, the definition of a late initiation was failure to initiate the task within 1 min following fault occurrence. The ANOVA results show that resource requirements had a significant effect on late task initiation.

Results from the ANOVA show that both resource requirements and the combination of flight path complexity and number of concurrent tasks created signifi-

TABLE 4
Summary of Experimental Results

	Experimental Factors			
	Number of Concurrent Tasks and Flight Path Complexity ($df = 3, 4$)		*Resource Requirements ($df = 1, 4$)*	
Response Variables	F	p	F	p
Task initiation (average response time)	5.85	.060	14.65	.019
Task initiation (late task initiation)	< 6.59	> .05*	27.00	.007
Task prioritization	32.08	.003	34.13	.004
RMS flight parameter errors	1.26	.400	3.04	.156

*Not significant; exact F and p values were not recorded.

cant effects on task prioritization. Therefore, task prioritization degrades as either one of these factors increases.

We calculated the RMS of deviations in flight parameters using data obtained from whole-mission information. Heading deviations were significantly affected by the combination of flight path complexity and the number of tasks; changes in mental resource requirements were significant to the altitude deviation. None of the other RMS deviations were significantly affected by either the resource requirements or the combination of flight path complexity and the number of concurrent tasks.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

We developed a taxonomy of CTM errors based on Funk's normative theory of CTM (Funk, 1991) and applied it in the analysis of NTSB aircraft accident reports and ASRS incident reports. We found CTM errors in 76 (23%) of the 324 accident reports analyzed and in 231 (49%) of the 470 incident reports. In a low-fidelity simulator study, we found that resource requirements (visual, manual, and mental) had a statistically significant effect on task initiation and task prioritization performance, and that the number of concurrent tasks coupled with flight path complexity had a statistically significant effect on task prioritization performance.

From our studies of aircraft accidents and incidents, we conclude that CTM is a significant factor in flight safety. And, as Raby and Wickens's (1994) results implied, our experiments confirm that increased resource requirements increase the likelihood of CTM errors—specifically, late task initiation and incorrect task prioritization errors.

We offer four recommendations. First, we recommend that pilots receive instruction concerning CTM and how to avoid CTM errors. More specifically, pilots should be made aware that in periods of high workload, when large numbers of concurrent tasks are competing for their attention, there is danger that they will not initiate important tasks promptly and that their attention will be drawn away from safety-critical tasks. Presumably, pilots can be taught to recognize these precursor conditions and to develop personal strategies to avoid CTM errors when these conditions are present. CTM instruction might most naturally fit into existing crew resource management training programs.

This recommendation is based on the assumption that our experimental environment, involving a low-fidelity simulator and (mostly) nonpilot participants is, at a very high level of abstraction, similar enough to the real commercial transport aircraft environment to warrant extrapolation. This assumption should be tested, so our second recommendation is that further studies of CTM be conducted using full-mission scenarios in high-fidelity training simulators with line pilots as participants. The objectives should be to validate our earlier findings, to search for other factors affecting CTM performance, to identify patterns of both good and bad CTM, and to attempt to link CTM errors with human cognitive characteristics, such as short-term (working) memory limitations.

Third, we recommend that research be conducted to develop and evaluate formal cockpit procedures to facilitate CTM performance, based on findings from the studies recommended previously. Such procedures might, for example, involve memory aids and elaborated versions of the well-known pilots' prioritization maxim: "aviate—navigate—communicate."

Finally, our fourth recommendation is that research be conducted to develop and evaluate a computational aid to facilitate CTM performance: a Cockpit Task Management System (CTMS). A CTMS might, for example, perform the following functions:

1. Maintain a current model of aircraft state and current cockpit tasks.
2. Monitor task state and status.
3. Compute task priority.
4. Remind the pilots of all tasks that should be in progress.
5. Suggest that the pilots attend to tasks that do not show satisfactory progress.

We must point out, however, that for any approach to be effective, net pilot workload must not increase. If personal strategies, formal procedures, or computational aids impose additional mental demands, there must be compensatory workload reductions. Otherwise, the supposed aids may actually lead to even worse CTM performance.

ACKNOWLEDGMENT

The preparation of the manuscript was partly supported by National Aeronautics and Space Administration, NASA Ames Research Center, Grant NAG 2–875. Kevin Corker was the technical monitor.

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Manuscript first received March 1995