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An Agent-Based Cockpit Task Management System: a Task-Oriented Pilot-Vehicle Interface

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ABSTRACTS

In today's highly automated aircraft, the role of the pilot has changed from an airplane controller to a system manager. As a system manager in a cockpit, today's pilot is in charge of a management-level activity called *cockpit task management* (CTM). According to earlier studies, pilot errors in performing CTM activities were significant factors in a large number of aircraft accidents and incidents. The primary objective of this research was to reduce CTM-related pilot errors.

A prototype pilot-vehicle interface called the *cockpit task management system* (CTMS) was developed and its effectiveness in improving CTM performance was evaluated. After the CTMS was implemented, it was integrated into a PC-based flight simulator to perform an experiment to evaluate its effectiveness. Eight volunteer subjects were used to collect performance data. The results of the experiment indicated that a statistically significant improvement was observed when the subjects flew with the assistance of the CTMS.

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1. INTRODUCTION

Safety is an important issue everywhere and at all times-in the home, in schools, and in industry. Aircraft safety has been a big issue to the public as well as to the aviation community. Although civil aviation operations are relatively safe and commercial air travel is reliable in comparison to other forms of transportation, aircraft accidents - whether or not they are fatal - draw immediate public attention and a great deal of concern.

The present research addresses the issue of aviation human factors. The discipline of aviation human factors encompasses "cockpit organization, crew interaction, fitness for duty (fatigue, health), judgment, sensory illusions, distraction, and complacency induced by reliability of equipment" (Lederer, 1988, p.xv). One of the major goals of human factors studies is reduction of the rate of human errors and development of the means to mitigate the undesirable consequences of errors when they occur. Though the statistics differ from one study to next, there has been general agreement that approximately two-thirds of all aircraft accidents are attributable at least partially to errors by flightcrew, or so-called *pilot errors* (Foushee & Helmreich, 1988; Nagel, 1988; Oster, Strong, & Zorn, 1992; Hawkins, 1993; Boeing Commercial Airplane Group, 1994).

In an aircraft cockpit, the pilot performs multiple, concurrent tasks to accomplish the flight mission. For example, the pilot may simultaneously lower the landing gear and communicate with air traffic control (ATC) while maintaining a correct descent rate. The pilot has two principal cockpit roles: controller and manager. Like a driver in an automobile, the pilot as controller performs operational-level tasks such as moment-to-moment manual control and activation/deactivation of automatic devices. As system manager, like a factory manager, the pilot performs such management-level tasks as monitoring system configurations and overseeing activities. In other words, the pilot is in charge of managing the multiple, concurrent flight tasks. Funk (1991) referred to this management-level activity as *cockpit task management* (CTM).

The basis for the present research follows from prior studies of CTM errors by Funk and his colleagues (Funk, 1991; Chou and Funk, 1993; Madhavan and Funk, 1993). Funk developed a preliminary CTM theory from the perspective of systems engineering; and Chou (1991) and Madhavan (1993) reviewed aircraft accident and incident reports, verifying the significance of CTM errors in those mishaps. To facilitate CTM and to reduce CTM-related pilot errors, the present study has included the development and evaluation of a prototype pilot-vehicle interface (PVI), the *cockpit task management system* (CTMS).

2. BACKGROUND

2.1 Cockpit Task Management (CTM)

CTM is "a process by which the flightcrew manages an agenda of cockpit tasks" (Funk, 1991, p. 277). CTM activities include:

1. task initiation,
2. task monitoring (i.e., assessing task progress and performance),
3. prioritization,
4. resource allocation, and
5. termination.

2.2 CTM Error

CTM errors occur when a flightcrew fails to perform CTM functions satisfactorily. After reviewing 324 air accident reports published by U.S. National Transportation Safety Board (NTSB), Chou (1991) found that CTM errors were involved in almost 25 percent of these accidents. Madhavan (1993) examined 470 incident reports published by Aviation Safety Reporting System (ASRS) run by National Aeronautics and Space Administration (NASA), and found CTM errors in almost 50 percent of the ASRS incidents. In the study, Madhavan developed a CTM error taxonomy (Table 1) and classified the CTM errors he found in the ASRS incident reports based on the taxonomy. The results of their research provided verification that CTM errors were significant factors in a large number of air accidents and incidents.

Table 1. Madhavans CTM error taxonomy (from Madhavan, 1993, p. 32).

General Level	Specific Level
Task Initiation	early
	late
	lack
Task Prioritization	incorrect
Task Termination	early
	late
	lack

Funk (1991), Chou (1991), and Madhavan (1993) proposed a pilot-vehicle interface (PVI), the cockpit task management system (CTMS), to facilitate CTM and to reduce CTM-related pilot errors. The CTMS can be viewed as an executive associate which would facilitate the pilots' managerial tasks.

2.3 Research Objectives

Cockpit automation is, in part, an attempt to eliminate or reduce pilot errors during flight. With the introduction of the state-of-the-art computer technology, automatic devices have become more reliable and sophisticated. However, no matter how advanced the automation, new types of pilot errors have been introduced and identified in aircraft accidents and incidents. These automation-related pilot errors have been a major research concern for many years.

It has been frequently observed that designers have sometimes attempted to eliminate pilot error by replacing humans, the sources of the error, with error-free automatic devices under a concept intended to "automate human error out of the system" (Wiener & Curry, 1982, p. 67). Even in highly sophisticated modern cockpits, however, humans are still responsible for operating and monitoring the automated devices to fly aircraft safely. Wiener (1987) asserted that "[cockpit] automation essentially relocates and changes the nature and consequences of human error, rather than removing it" (p. 179). The advanced cockpit "calls for more programming, planning, sequencing, alternative selection, and more thinking, or in psychological terms, more cognitive processing" (Wiener, 1988, p. 447). As a result, changes in the characteristics of cockpit tasks have increased the pilots mental workload, especially around terminal areas when the pilot is busy. Since the designers of automatic devices have "emphasized reducing manual workload, not accounting adequately for mental workload" (Wiener, 1988, p. 447), however, the pilots management-level workload that requires greater mental activity has been increased, while the operational-level workload has been reduced by automating routine manual tasks. Sufficient evidence exists to indicate that the solution of automation-related pilot errors in the future cockpits should be directed toward assisting the pilot with management-level tasks. The CTM concept is an approach which addresses this issue.

Funk (1991), Chou (1991), and Madhavan (1993) proposed a pilot-vehicle interface (PVI), the *cockpit task management system* (CTMS), to facilitate CTM and to reduce CTM-related pilot errors. The objective of the present study include:

1. Determination of the feasibility of CTMS implementation through the development of a prototype CTMS; and
2. Evaluation of CTMS effectiveness for improvement of CTM performance.

3. METHOD

A prototype CTMS was designed based upon the recommendations provided by Funk (1991), Chou (1991), and Madhavan (1993). Concepts of object-oriented design (OOD) and distributed artificial intelligence (DAI) were employed in developing the CTMS. The CTMS was then integrated into a PC-based flight simulator for experimental evaluation of system effectiveness. Volunteer subjects flew scenario simulations both with and without the CTMS. Performance data was collected and analyzed to evaluate CTMS effectiveness.

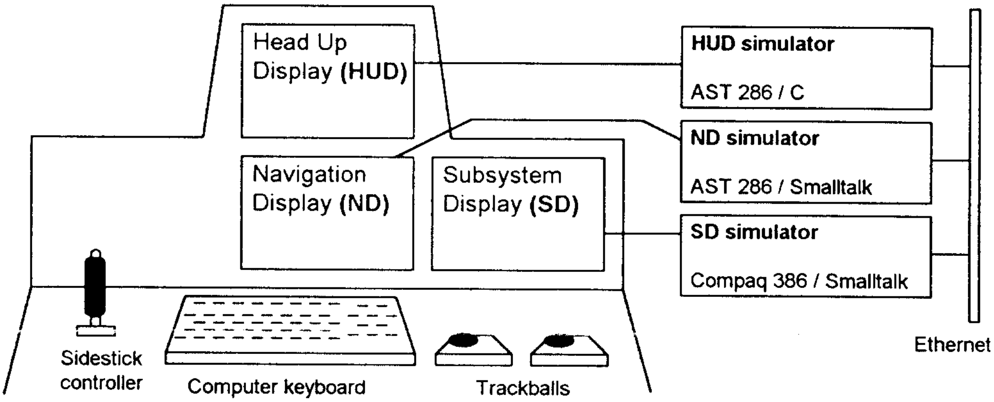

Figure 1. Overall flight simulator structure.

3.1 Flight Simulator

The flight simulator used for this research was a small, fixed-based model of an aircraft cockpit for a single pilot (Figure 1). It was developed by modifying an existing flight simulator used for a previous CTM study (Chou, 1991). The simulator consisted of three personal computers (each with its own monitor), a computer keyboard, two trackballs, and a sidestick controller. All of the simulator computers were linked via Ethernet, using the TCP/IP communication protocol.

The top monitor (Figure 1) showed head up display (HUD) information. In a real airplane, such information about flight data as attitude, heading, altitude, and airspeed is displayed on a HUD. As the name implies, a HUD permits the pilot to monitor flight data while keeping his/her “head up” to be able to maintain out-the-window observation. The simulator HUD displayed such information as : current and command heading, airspeed, and altitude ; a pitch ladder indicating pitch and roll angles; aircraft latitude and longitude ; and autopilot status (engaged or disengaged).

The bottom and left monitor provided a navigation display (ND) consisting of four panels: a horizontal situation indicator (HSI), an automatic flight control (AFC) communication panel. The HSI displayed an aircraft-centered moving map consisting of an aircraft symbol, the current flight path, and waypoint symbols and names. It also displayed the current aircraft position, active waypoint data, weather radar data, and an expanded compass rose. The AFC and the source select panels displayed computer-generated button and knob images. These buttons or knobs were used to set the HSI display or a source selector to the desired mode. A trackball was used to both “push” the buttons and “turn” the knobs. The ATC communication panel provided a simplified data-link system for electronic, rather than verbal, communication with a simulated air traffic controller.

The subsystem display (SD) consisted of six control panels and two display panels. The SD control panels were used to control such aircraft subsystems as the engine, the hydraulic system, and the electrical system, as well as the landing gear and flaps. As for the ND, simulated buttons or knobs in the panels were "pushed" or "turned" using a trackball. The SD display panels provided a simple EICAS (engine indication and crew alerting system) and synoptic displays of aircraft subsystems such as engine, fuel system, hydraulic system, electric power system, and landing gear.

3.2 Cockpit Task Management System (CTMS)

Based on the proposed requirements of Funk (1991), Chou (1991), and Madhavan (1993), specific goals for the CTMS development were established. These were to help the flightcrew prioritize tasks, initiate tasks, terminate tasks, interrupt tasks, and resume interrupted tasks. To achieve these goals, functional requirements for the CTMS were established. These were to provide the flightcrew with information about task state, task status, task priority, and task relationships.

The CTMS was developed on the fourth personal computer, and added into the existing flight simulator (Figure 2). It was implemented using Smalltalk, an object-oriented programming language. Concepts of object-oriented design (OOD) and distributed artificial intelligence (DAI) were employed in CTMS implementation.

The CTMS was a knowledge-based system in which problem-solving knowledge is distributed among software units referred to as "agents". Simulated aircraft subsystems and pilot tasks were represented in the CTMS by "system

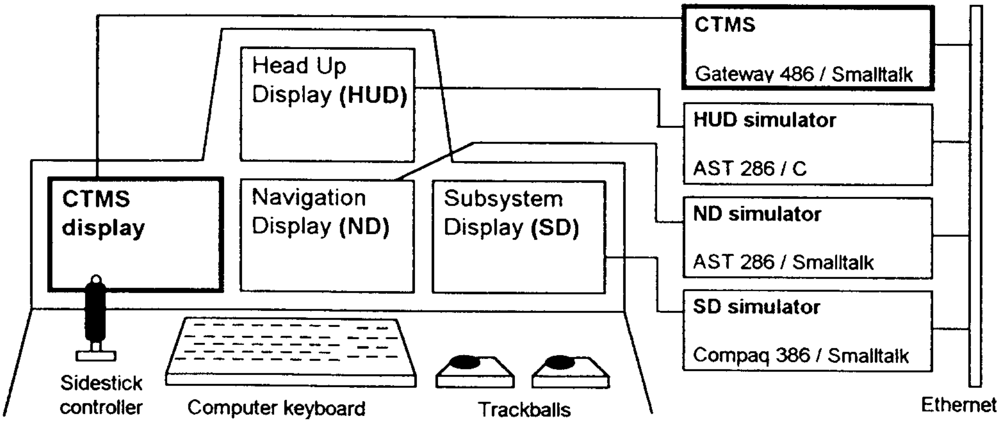

Figure 2. Overall flight simulator structure after adding the CTMS.

agents" (SAs) and "task agents" (TAs), respectively.

An SA was a representative of an aircraft subsystem. A subsystem SA received state information about its corresponding subsystem from the flight simulator, releasing this information when requested. In the CTMS, an SA was implemented by an instance of a Smalltalk class, and the specific behaviors or knowledge of the SA were implemented in the methods (i.e., procedures) of the class.

Task agents were responsible for monitoring the performance of corresponding flight tasks. Like an SA, a TA was implemented by an instance of a Smalltalk class, and its specific behavior or knowledge was implemented in the methods of the class. This knowledge allowed each TA to determine when its task should be started, when it should be terminated, and how its status (i.e., performance-satisfactory or unsatisfactory) should be assessed.

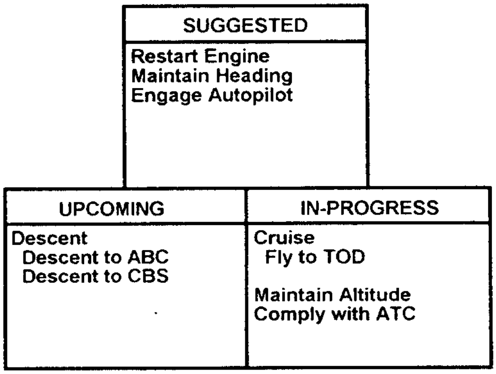

Figure 3. Snapshot of the CTMS display.

From the pilots perspective, the core unit of the CTMS was its display which provided information about all tasks with respect to task state, status, and priority (Figure 3). The display consisted of three sections: (a) UTD (upcoming task display), (b) ITD (in-progress task display), and (c) STD (suggested task display). The UTD listed those tasks that should be started soon (e.g., an upcoming descent). The ITD listed those tasks that should actually be in progress (e.g., an ongoing cruise). The STD listed any tasks that require immediate attention due either to poor performance or urgency. With this three-section arrangement, task state (upcoming, in-progress, or suggested) was presented using location coding.

Task status (satisfactory or unsatisfactory performance) was indicated by the use of color coding. That is, if the performance on a task was satisfactory, the name of the task was displayed in green; if it was unsatisfactory, a yellow or red color was used, depending upon the importance of the task.

In addition to task state and status, task priority information was presented on the STD, the topmost of the three CTMS display sections. That is, names of the suggested tasks (those needing immediate attention) were listed in order of the priority of the tasks, with higher priority tasks being placed higher in the list. Figure 3 shows a snapshot of the CTMS display.

3.3 Experiment

After the CTMS was implemented, an experiment was performed to evaluate its effectiveness in improving CTM performance. Twelve volunteer subjects were used for the experiment. The first four subjects were used for a pilot study to check the readiness of the experiment, and the remaining eight subjects were used for the data collection runs.

A balanced experimental design was developed for the data-collection flights (Table 2). To compare subject performances between flying with and without the CTMS, each subject flew two data-collection scenarios-one with the CTMS and the other without it. The experimental procedure was administered in two sessions: a training session and a data-collection session. After a four-hour first-day training session followed by a two-hour second-day training session, each subject flew two 50-minute data-collection flight scenarios with a 5 to 10 minute break between flights.

Four measurements were considered for the evaluation of the subject performance in the flight simulator:

1. task prioritization,
2. pilot response time,
3. task completion, and
4. aircraft controls.

The first three of the four measurements reflected the three elements in the CTM error taxonomy discussed in the previous chapter (Tablel): task prioritization, task initiation, and task termination. Subject performances in the use of aircraft controls-including heading, altitude, and airspeed controls-were measured because they were essential to the comprehensive measurement of overall pilot performance. Subject performances from the 16 scenario flights flown by eight subjects were collected. The simulator log files, which recorded pilot actions and performance measures, as well as videotapes were used to collect performance data.

Table 2. Experimental design for data-collection flights.

Subject Number	Run Number	Scenario Type	Factors of CTMS
1	1	A	with CTMS
	2	B	without CTMS
2	3	B	without CTMS
	4	A	with CTMS
3	5	A	without CTMS
	6	B	with CTMS
4	7	B	with CTMS
	8	A	without CTMS
5	9	B	with CTMS
	10	A	without CTMS
6	11	A	without CTMS
	12	B	with CTMS
7	13	B	without CTMS
	14	A	with CTMS
8	15	A	with CTMS
	16	B	without CTMS

4. RESULTS

In association with the four performance measurements described above, data for the following four variables were collected: (a) the ratio of misprioritizations to opportunities for misprioritization, (b) the time required for subjects to first respond to unsatisfactory flight tasks, (c) the proportion of unsatisfactory aircraft control time during a flight, and (d) the total number of flight tasks the subjects failed to complete by the end of the simulator flights.

One of the goals of this research was to determine if the CTMS provided effective flight-task assistance during simulated flights. To arrive at this determination, mean subject performances flying with and without the CTMS were compared. As shown in Figure 4, when subjects flew with the assistance of the CTMS, the mean task misprioritization rate was reduced by 41%, the mean subject response time was reduced by 18%, the exercise of mean unsatisfactory aircraft controls was reduced by 24%, and the average number of incomplete tasks during simulator flights was reduced by 82%.

In addition to comparing the subject performance averages, a statistical analysis of the collected data using an analysis of variance (ANOVA) was performed as an additional means of determining whether use of the CTMS resulted in improved subject performance. Since the hypothesis test using the ANOVA was based upon the expectation that performances with the CTMS would be better than performances without the CTMS, a one-tailed test was employed. A type I error, denoted by , for both 0.1 and 0.05, was used insofar as this form has gained

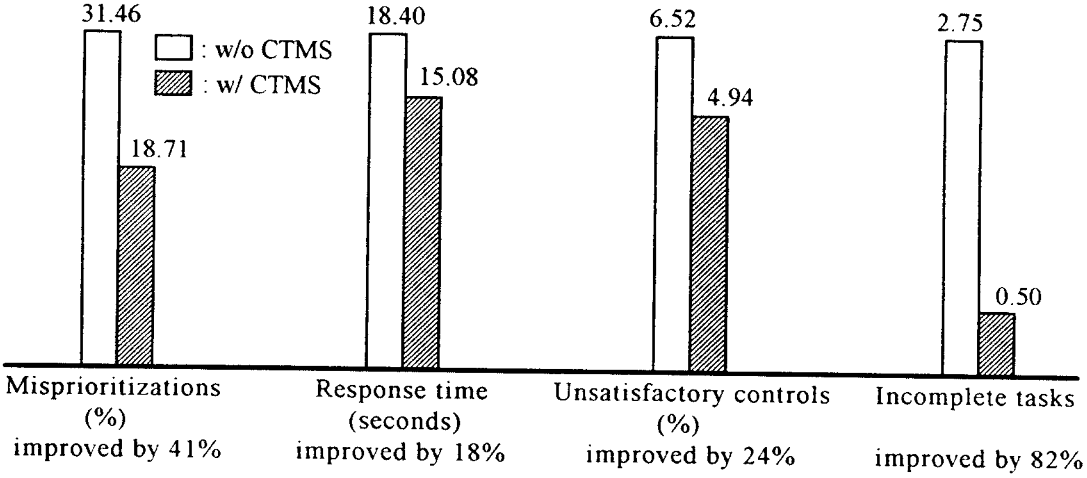

Figure 4. Comparison of mean subject performance for flights with and without CTMS assistance. Note that the shorter the bar, the better the performance.

acceptance for use in typical statistical analyses. In such analyses, the results of a hypothesis test are reported as a number called the "p-value"-a measurement of the credibility of the hypothesis test. A type I error α, , and a p-value are used to determine whether the null hypothesis, denoted by Ho, can be rejected. Since the principal concern of this experiment was CTMS effectiveness, as indicated by the p-values for the treatment effect, only these values are presented (Table 3).

Table 3. ANOVA p-values for treatment effect and hypothesis test results for $\alpha=0.1$ and $\alpha=0.05$ (Ho: $\mu_0=\mu_1$; Ha: $\mu_0>\mu_1$).

Misprioritization	0.066	Reject Ho since $p<\alpha$	Do not reject Ho since $p>\alpha$
Response time	0.093	Reject Ho since $p<\alpha$	Do not reject Ho since $p>\alpha$
Aircraft controls	0.052	Reject Ho since $p<\alpha$	Do not reject Ho since $p>\alpha$
Incomplete tasks	0.009	Reject Ho since $p<\alpha$	Reject Ho since $p<\alpha$

From the results of the hypothesis test, the p-value for incomplete tasks indicated that there was a significant improvement for task completion performance when subjects flew with the assistance of the CTMS, whereas the p-values for the remaining three measurements for task prioritization, task initiation, and aircraft controls were "suggestive" with respect to evidence of performance improvement.

5. DISCUSSION

Results of the experiment indicated that a CTMS-like PVI is potentially effective in improving the pilot's CTM performance in a cockpit. However, there were a number of limitations with regard to the present study, which should be overcome through more research efforts for a real-world CTMS to become a reality.

5.1 CTMS Effectiveness

A prototype CTMS was successfully developed for the present research project, and the experimental results indicated that subject performance improved when flying with the assistance of the CTMS. However, since the present study was performed in a highly simplified aircraft operating environment, the success of the CTMS development cannot be generalized to guarantee the feasibility of the implementation of this type of PVI for an extremely complex real-world aircraft environment.

Despite the fact that a real-world CTMS may not be possible in the near future, what was learned from and demonstrated by this research should prove valuable to future CTM studies.

5.2 Research Contributions

Through the successful development of a prototype CTMS, a feasible approach to the implementation of a real-world CTMS was demonstrated. Although the development of a CTMS for real aircraft will require a major upgrade from the CTMS developed for the present research, the fundamental and essential aspects of a CTMS seem to have been adequately demonstrated by the research findings.

Also, the potential significance of a CTMS-like PVI was verified. The results of the experiment indicated that the CTMS developed provided effective CTM performance assistance. Given that performance testing was conducted in an experimental environment, the potential effectiveness of a real-world CTMS was demonstrated.

Lastly, this research will provide an eventual contribution to aviation safety. As the potential usefulness of the CTMS is verified by improvement of the pilot's CTM performance as well as general aircraft controls, such a pilot aid could be an effective enhancement of aircraft safety.

5.3 Research Limitations

As is true of most academic research performed in small laboratories, a number of limitations were encountered throughout this project. The principal limitation was lack of realism, resulting primarily from use of the existing flight simulator. For example, although the sidestick controller (Figure 1) in a real aircraft is located at the middle or right-hand side of the pilot, the one in the flight simulator used in this research was located at the left-hand side because the pilot need to use his/her right hand to control trackballs. Since the PC-based low-fidelity flight simulator used cannot represent the activities of a real-world aircraft, developing a realistic CTMS for such an environment was not possible.

Size and qualification of the sample was also limited. Although confidence in the results of an experiment would have increased as sample size was increased, only eight subjects were used for the collection of performance data, primarily because of time and effort required to recruit volunteer subjects. In addition to limited numbers, the qualifications of the subjects were also limited. To obtain more realistic performance data, the use of licensed pilot volunteers was preferred, but only four licensed pilots were available from among the eight subjects used in the data-collecting sessions.

Finally, the validity of the experimental results was limited. Though every effort was made to conduct experiments free of bias, it was always possible that biased output could have been created. That is, the experimental results could be biased as a result of: (a) variant conditions in the training sessions (e.g., condition of the trainer and trainees), (b) environment of the experiment (e.g., noise, temperature, or time-of-day), and (c) variant conditions in the data-collecting sessions (e.g., subject ability to concentrate attention upon the tasks).

6. CONCLUSIONS

In the effort to mitigate CTM-related pilot errors, a prototype pilot-vehicle interface (PVI) called the cockpit task management system (CTMS) was developed for this research. After implementation, the CTMS was integrated into a flight simulator to perform an experimental effectiveness evaluation. Eight subjects were used to collect performance data for the experiment. Four performance measurements were considered for the evaluation of subject performance: (a) task prioritization, (b) pilot response time, (c) aircraft controls, and (d) task completion.

The results of the mean subject performance improvements, in conjunction with these p-values, suggested that significant improvement was observed when subjects flew with the assistance of the CTMS. Therefore, the experimental research described demonstrated the potential value of a CTMS-like PVI for aircraft applications.

This study was successful due in large part to the simplicity of the simulated aircraft environment and tasks. Nonetheless, the research findings of this study will be useful for general PVI studies as well as for the future CTM studies. By the same token, the ultimate contributions of the present research are not necessarily confined to the issue of aviation safety, but the principles derived could be extended to the safety issue everywhere-in the home, in schools, and in general industry as well.

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