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COMPARISON OF HELICOPTER COPILOT WORKLOAD WHILE USING THREE NAVIGATION SYSTEMS DURING NAP-OF-THE-EARTH FLIGHT

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Three different generic navigation systems were examined for their effects on helicopter copilot/navigator workload and performance during nap-of-the-earth (NOE) flight. The navigation systems examined were: (1) the conventional 1:50,000 scale topographic hand-held map, (2) a Doppler navigation system in conjunction with a hand-held map, and (3) a projected map system driven by Doppler signals in conjunction with a hand-held map. Eighteen pilots performed copilot/navigator duties in an Army JUH-1H utility helicopter flown by a laboratory research pilot. Data collected included measures of navigation performance, pilot-copilot communications, and copilot/navigator eye movements.

The results indicate that automatic navigation systems like the ones used here improve navigation performance by enabling the aircrew to reach their destination with reduced in-flight delays, at a faster airspeed, and with fewer and smaller navigation errors. The number of verbal exchanges between the copilot and pilot was reduced when using the Doppler system versus the hand-held map alone. Subjects who used the Doppler also spent less time navigating. When using a projected map system, copilot/navigators experienced a lower level of visual workload and spent 10% more time looking outside the cockpit. With all navigation systems, more than 80% of the copilot's time was spent navigating, over 20% of the aircrew's time was spent in navigation communications, and less than 10% of their time was visual "free time" that could be used to attend to other tasks.

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Human subjects participated in this study after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Reg 70-25 on Use of Volunteers in Research.

Major Krueger is presently assigned to Headquarters, U.S. Army Medical Research and Development Command, Fort Dietrick, Frederick, Maryland.

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INTRODUCTION

In the 1970's, sophisticated radar tracking systems and anti-aircraft weapons brought about significant changes in Army helicopter flight tactics. It is now imperative that A~my aviators fly helicopters beneath the radar threat at very low altitudes where they can capitalize upon the cover and concealment of terrain features and vegetation. Terrain flight techniques help pilots to avoid visual, optical or electronic detection by the enemy and thus enhance the chances of helicopter survivability on the battlefield.

The US Army identifies three modes of terrain flight: (1) low level, (2) contour, and (3) nap-of-the-earth (NOE). The most difficult of these modes to perform and the one most likely to be used in a hostile environment is NOE flight. NOE is described as flight at varying airspeeds as close to the surface of the earth as vegetation, obstacles and ambient light will permit while generally following the contours of the earth (Department of the Army 1979). In addition to being a tough regimen of flight for the pilot, this mode of terrain flight also makes navigation very difficult for the aircrew.

AIRCREW DUTIES

The large number of tasks that must be performed while flying NOE contributes to the navigation problem. Some of these tasks are peculiar to NOE flight; others are also common to other types of flight.

At NOE altitudes, the pilot's primary duty is to fly the aircraft, to keep it clear of obstacles, and to follow and maintain the ground headings provided by the copilot/navigator or a trained non-pilot crewmember/observer. The pilot is also expected to assist in navigation by pointing out significant terrain features to the copilot/navigator, monitoring the radios, and making radio calls as appropriate.

The copilot/navigator also has a considerable number of duties to perform. The copilot's primary duty is navigation. He or she must know the position of the aircraft relative to the map at all times. The copilot must select terrain features on the map for checking aircraft position, identify these terrain features outside the aircraft, compare actual flight path with intended flight path, check the map for boundaries, controlled, restricted and danger areas, insure airspace management is maintained, anticipate unplanned changes, plan alternative courses of action, and consider route changes that may enhance aircraft masking. From the information gathered in performing these tasks, the copilot must give the pilot frequent, precise, navigation instructions.

In addition to the above navigation duty, the copilot must also assist the pilot in hazard and obstacle avoidance by telling him what to expect ahead, monitor the aircraft instrument panel, assist the pilot in radio monitoring, make radio calls, and perform any other tasks specific to the type of helicopter (e.g., attack, scout, utility or cargo), and the mission (e.g., target acquisition, fire control coordination, or attack with weapons firing). Performing many of the above listed duties leaves the copilot only short time periods to perform any one task such as analyzing the map. Unfortunately, the task of correlating map information with the terrain passing below in NOE flight is not easily accomplished with only short glimpses at most maps available to a helicopter crew.

MAPS

Certain characteristics of the current topgraphic maps used for NOE navigation make them less-than-ideal navigation instruments. Topographic maps provide a perpendicular view of the terrain (looking from the top down). However, at NOE flight levels, the helicopter aircrew has an oblique view of the terrain. Thus, reading the map and correlating its terrain representation with the actual terrain viewed is a difficult task. A large pond which is readily apparent on the map may actually be only 100 meters from the helicopter, but trees masking the aircraft from enemy detection may also be masking the pond from the view of the copilot/navigator.

The standard 1:50,000 scale topographical map typically used for NOE navigation is a sheet approximately .75 m long by .5 m wide which depicts a ground area of 28 by 24 km. Unfolded in the cockpit, these large map sheets cannot be handled easily without interfering with other flight tasks. Furthermore, because of the limited terrain coverage on any single map, several adjoining sheets may have to be used for one mission. This problem may be overcome by taping several sheets together and folding them such that a smooth visual transition may be made from one map sheet to another. Nevertheless, the bulkiness of these folded, large scale map sheets is an inconvenience to the navigator.

The handling problem associated with map sheets is compounded at night when a light is needed to read the map. If the navigator chooses to read the map with a white light, he will partially destroy his dark adaptation. Reading a map with a red light reduces this problem, but it also creates a contrast problem, making it difficult to read all map areas.

Reading a map while wearing night vision goggles is also difficult due to the limited depth-of-field of the goggles. If the goggles are focused for optimum viewing outside the cockpit, then anything observed inside the cockpit will be out of focus. Consequently, the goggles must be focused to look at the map and then refocused before looking outside the cockpit.

STRESS AND FATIGUE

All of the above problems with NOE navigation are compounded by the extraordinary stress and fatigue that NOE aircrews experience. Bailey (1964) reports that higher stress levels are experienced by an NOE aircrew because of their operation in close proximity to the ground where a very low probability exists for a safe landing in response to in-flight emergencies. Dowd and Brunstetter (1980) found terrain following and terrain avoidance flying to be the most stressful of numerous helicopter maneuvers and flight modes examined, even among experienced helicopter test pilots. Mean copilot heart rate was 108 beats per minute while at terrain following altitudes. The test pilots reported that the high stress experienced while flying close to the earth was due to the high workload demand on pilot attention , skill, and alertness. When operating close to the earth, the aircrew must constantly detect and avoid hazards such as utility poles, telephone or electrical wires, trees, etc.

Associated with the higher levels of aircrew stress during NOE flight is pilot fatigue. In a survey of student and instructor helicopter pilots, Duncan, Sanders, and Kimball (1980) estimated day terrain flight to be 1.3 times as fatiguing as standard day flight; and night terrain flight to be two times as fatiguing as standard day flight. Fatigue can affect individuals in several ways. It can cause slowed response, a reduction in attention and memory span, and impaired mental and manual dexterity. As a result, navigation skills which rely on quick responses and logical decision making could be degraded.

DISORIENTATION

Geographic disorientation adds to the stress and fatigue experienced by the NOE aircrew. McGrath (1964) reports that aircrews experience marked emotional stress when they become disoriented. This stress could be very high in a combat situation when not only would the crewmembers not know their position, but they would also be unsure of their proximity to enemy positions.

Geographic disorientation is not an uncommon event during NOE flight. It is more prevalent than most pilots admit to or than many accident reports would indicate. Holman (1978) found aircrews that received NOE navigation training became disoriented, on the average, once every 5.5 km in NOE flight. McGrath (1964) points out examples from studies in which the aircrews became disoriented within a few minutes after leaving a checkpoint. Other studies report aircrews being disoriented only a few meters off course (Barnard and others 1976).

In reviewing several of his own studies, McGrath (1964) examined reasons for disorientation. He concluded that the most common reason for disorientation is the difficulty the aircrew experiences in trying to select, detect, and identify terrain features or navigation checkpoints. Other factors contributing to aircrew disorientation include the lack of any conspicuous terrain features in some areas, out-of-date maps, workload from other flight duties which leads to devoting insufficient attention to the map, incomplete navigation preparation prior to takeoff, ineffective aircrew communication, increased stress levels, decreased security and confidence, and unintended detours from intended flight path (Bailey 1964, Barnard and others 1976, and McGrath 1964).

The above mentioned problems are common when flying during the day in good weather. It is not difficult to imagine a further increase in navigation difficulty when flying at night or in bad weather where visibility is markedly reduced.

NAVIGATION AIDS

To aid the aircrew in maintaining proper orientation and to decrease navigation workload, the US Army has considered installing automatic navigation equipment in some of its helicopters. In an Army report, McGrath (1976) reviewed the literature on available navigation systems that might offer assistance to helicopter pilots. When each system was matched against such criteria as cost, weight, area coverage provided, vulnerability to enemy interference/destruction, etc., only two systems were deemed to be suitable for Army aviation.

One system suggested for use in Army helicopters was a self-contained, onboard Doppler radar navigation system. A Doppler radar navigation system calculates changing aircraft position from a known starting point by measuring aircraft velocity as a function of the frequency shift in the radar waves emitted and received by the system. The second system seen as a viable candidate was the NAVSTAR global positioning satellite system. However, this system is not yet operational and is not likely to be for some time. Both of these systems would provide navigation information to crewmembers in an alphanumeric format.

McGrath's 1976 report also describes available pictorial navigation displays that provide navigation system information to the aircrew in a pictorial format based on information from an aircraft position sensor such as the Doppler. Two pictorial displays offered potential in the Army aviation environment: roller map displays (paper maps on rollers driven by servomechanisms) and projected map displays (filmstrips of maps driven by servomechanisms). Various versions of these two navigation devices and the Doppler have been available for several years and have been tested for effectiveness.

FLIGHT TESTS OF NAVIGATION SYSTEMS AND MAP DISPLAYS

Two map display tests were conducted by the French Land Army Aviation League in the mid 1960's (Griselin 1966 and Crouget 1966). These tests were primarily concerned with the accuracy of map displays and not the complete man-machine system. The information from these tests is limited because the reports were labeled "restrictive" or "not available for distribution." However, letter reports from the manufacturers of the two moving map displays tested indicate that the French aviators found the map displays to be "an indispensible complement to the Doppler system" and that the aviators were pleased with the systems.

In 1968 and 1969, a series of flight tests was done in the United Kingdom (UK) on two projected map displays and a roller map display (Emtage and Carter 1968a, Emtage and Carter 1968b, Tayler and Carter 1969). The results of these reports were restricted to the manufacturers of the equipment and the UK military establishments. However, from results released by one of the manufacturers of the equipment tested, it is apparent that these tests were also mostly concerned with the accuracy of the equipment and not its specific role as an aid to the aircrew. The only aircrew oriented information available from the tests was a statement that the pilots "appraised the map display as a valuable aid to helicopter navigation, particularly at low level and in conditions of bad weather and poor visibility" (McGrath 1976).

Lewis and Anderson (1969) compared a projected map system against a hand-held map for the Canadian Armed Forces. Their tests consisted of straight-line helicopter flights 25 feet above obstacles at 100 knots. They reported that the largest errors were made while using the hand-held map. They concluded that "only an automatic navigation system can ensure that gross errors will not occur." No measures of navigator workload were indicated in their report.

The US Air Force did a study on a roller map display (McKechnie 1970). The test flights were conducted in fixed wing aircraft flying 2,500 feet above the ground at 120 knots. The standard 1:50,000 scale topographic map was compared to a roller map display containing 1:50,000 scale topographic maps and a roller map display containing 1:50,000 scale picture maps. They reported that the mean distance and standard deviation off course were largest for the pilots using the hand-held map.

The most recent studies on the use of automatic navigation systems were done by the US Army. In 1977, the US Army Aircraft Development Test Activity (USAADTA) did a developmental flight test of the Singer-Kearfott (see footnote) Lightweight Doppler Navigation System, LDNS AN/ASN 128 (Carter and others 1977). The system was flight tested in a UH-1H Army utility helicopter, a AH-1G Army attack helicopter, a CH-47C Army cargo helicopter, and a U-21A twin engine Army airplane for a combined total of over 700 hours. Using the LDNS for navigation, six profiles were flown. The test report stated that the Doppler gave the aviators "repeatable, accurate navigation information that facilitated the location of landing zones, resupply points, and enemy positions." The report also noted that the "LDNS was best suited for straight-line navigation and for rapidly redirecting the route of flight during the en route portion of a mission where it greatly decreases the workload of the aircrew." However, aviators accomplished NOE navigation by using the hand-held map as the primary navigation device and the Doppler was used only to check the exact position of the aircraft.

USAADTA also did a concept evaluation of a Computing Devices Company of Canada Projected Map System (PMS) for the purpose of determining the operational potential of a projected map system for NOE flight (Weseman 1977). The PMS was compared to a Ryan Doppler system and a standard 1:50,000 scale hand-held topographic map. USAADTA found that pilots using a PMS navigated a NOE course in approximately one-half the time taken by pilots using a Doppler or a hand-held map. Furthermore, no disorientations occurred while using the PMS in 27 day flights and 15 night flights. However, a total of 25 disorientations occurred in the same number of day and night flights when the

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See Appendix A for a manufacturer of equipment list.

Doppler and the hand-held map were used. USAADTA concluded that the reduced navigation workload experienced when using a PMS enables a single pilot to perform both the flying and the navigation duties during NOE flight.

In the Carter and others test, the primary performance measurement was the distance from the actual destination when relying solely on the Doppler. In the Weseman test, navigation performance when using a PMS, a Doppler and/or a hand-held map was measured by the time to complete a NOE course, the number of disorientations on a NOE course, and the time to recover from each disorientation. The experimental design of this latter test precluded conduct of useable statistical analysis of the performance data. Although aviator workload was discussed in both studies, no objective quantitative workload data were collected. Other shortcomings of these tests included a question of how much familiarity the test pilots had with the courses flown and the possibility that the courses were not flown at true NOE levels but at some combination of the three types of terrain flight levels.

To date, the tests on automatic navigation systems have only established that available systems are accurate and do compliment the aircrew's navigation performance. The question that must be answered next is: Do these systems reduce the high workload imposed by NOE navigation while at the same time improving navigation performance? This question has not yet been answered with objective data collection and statistical analyses.

The only objective data collected on navigator workload to date seem to be those of Sanders, Simmons, and Hofmann (1979). They measured navigator/copilot eye movements and reported the visual workload of subjects navigating while using a hand-held map during NOE flight. They reported: (1) navigation duties occupied 92% of the copilot/navigator's visual time; (2) instrument monitoring occupied 4% of their visual time; and (3) 3% of their visual time was "free time" (not engaged in navigation or instrument monitoring duties).

The lack of objective navigation workload data on automatic navigation systems led the Program Manager's Office of the Advanced Attack Helicopter to request the US Army Aeromedical Research Laboratory (USAARL) to collect such data on automatic navigation systems which would be applicable to helicopter NOE operations.

The objective of this project was to compare the copilot/navigator workload and performance effects of a Doppler navigation system and of a projected map system to those of a hand-held map system. Two statistically testable hypotheses were formulated: (1) navigation workload does not change as a function of navigation system; and (2) navigation performance does not change as a function of navigation system.

MATERIALS

EQUIPMENT

Aircraft

The US Army Aeromedical Research Laboratory's JUH-1H utility helicopter, specifically instrumented for in-flight data collection, was used in the study (see Figure 1). An Army JOH-58A scout helicopter and crew flew overhead to provide supplementary safety coverage for the NOE flights.

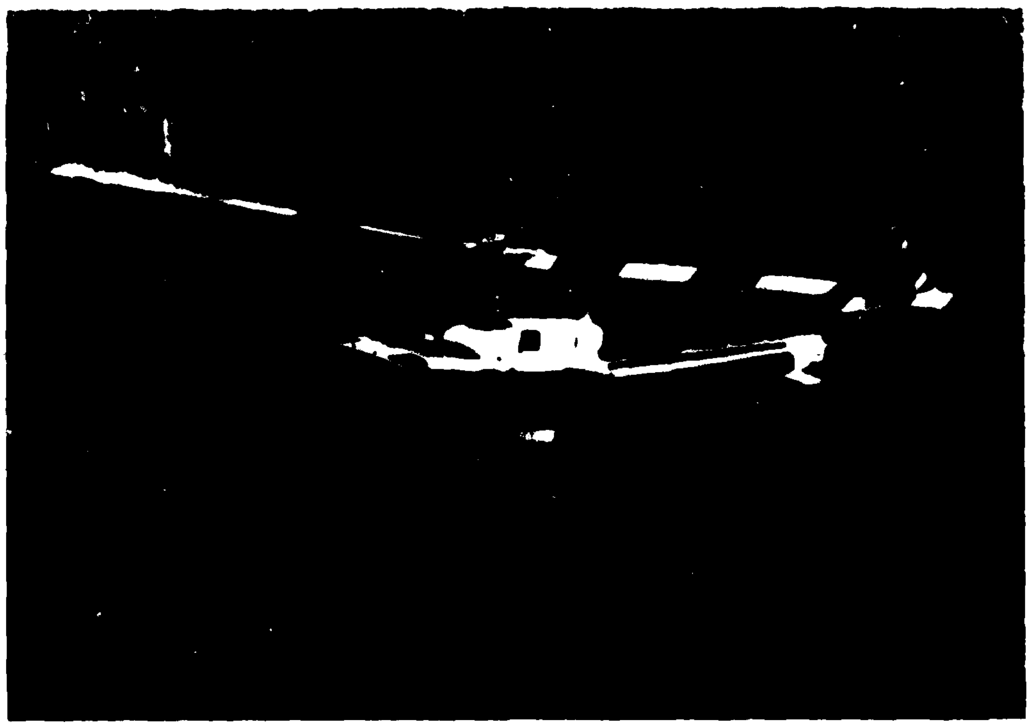

FIGURE 1. JUH-1H Utility Helicopter.

Navigation Systems

Three navigation systems were used in the study. Two automatic dead reckoning navigation systems (a Doppler radar and a projected map system) were installed in the JUH-1H helicopter. The third system, the baseline system, was the standard Army 1:50,000 scale, hand-held, topographic map. The three systems are described in detail below.

Doppler System: The Doppler used in this study was an engineering development model, Lightweight Doppler Navigation System (LDNS AN/ASN 128-XE 2), produced by the Kearfott Division of the Singer Company. This Doppler is an earlier version of the AN/ASN 128 Doppler that Singer presently produces for military use. The LDNS is a completely self-contained navigation system that does not require any ground-based aids and is capable of providing position information anywhere in the world by tracking from a known starting point. The LDNS used aircraft heading and vertical reference information inputs, and transmitted and received radar waves to calculate and provide aircraft groundspeed, track angle, position, and checkpoint steering information at flight altitudes from ground level to higher than 10,000 feet above the ground.

The LDNS consists of three components: (1) a receiver-transmitter antenna (mounted in the underside of the aircraft fuselage) that transmits and receives Doppler radar signals; (2) a signal data converter (mounted in the aircraft avionics bay) which measures the Doppler frequency shift between the transmitted and received Doppler signals and digitizes this information as well as the aircraft heading, pitch, roll and true airspeed information; and (3) a computer-display unit (CDU). The CDU is the only component that must be housed in the cockpit (see Figure 2).

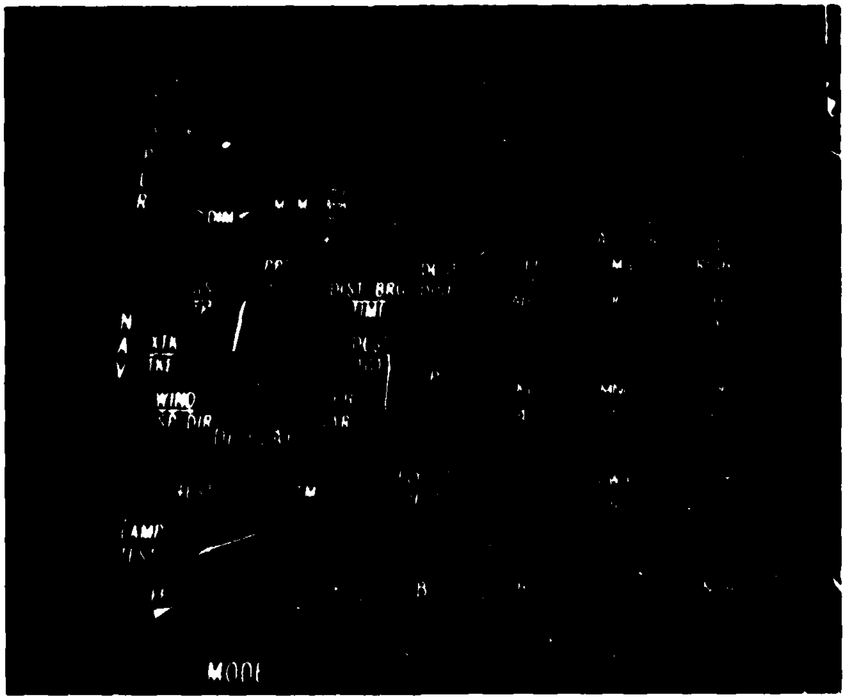

FIGURE 2. Computer-Display Unit of the Lightweight Doppler Navigation System

For this study, the following navigation information could be displayed on the CDU: (1) latitude/longitude or universal transverse mercator (UTM) grid coordinates of the helicopter present position or the coordinates of any of ten preprogrammed checkpoints; (2) the distance, bearing, and time to any of ten preprogrammed checkpoints; (3) groundspeed and track angle (relative to true north); and (4) crosstrack distance and track angle error from the straight-line course to a destination. When true airspeed is available, the CDU can also provide wind velocity.

The LDNS includes the following features: (1) a display luminance control which allows for viewing the displays in bright sun or with night vision goggles; (2) built-in test equipment with malfunction lights and display codes that indicate and pinpoint malfunctions; (3) non-volatile memory; (4) update capabilities; (5) target storage capabilities; and (6) backup mode of operation capabilities in the event of partial system failure.

The system may be updated to correct for discrepancies between indicated aircraft location versus actual aircraft location by depressing two buttons (KYBD then ENTR, see Figure 2) when the aircraft is over an area for which the grid coordinates are stored, or, by entering a 13 character alphanumeric that requires an 18 keystroke input when the update point is not in memory.

Coordinates of a target can be stored by pressing one button (TGT STOR) when the aircraft is over the target. With this action, the system places the target coordinates in one of four memory locations and displays the location to the pilot. A more involved target storage procedure allows the user to select the specific memory location for the target coordinates.

Projected Map System: The Projected Map System (PMS) used in the study was manufactured by Computing Devices Company. The PMS provides steering, position, and other navigation information to the aircrew via a pictorial display and alphanumeric readouts.

The PMS is not a complete automatic navigation system in itself. It requires inputs of groundspeed and drift angle from a sensing system such as the Doppler, and heading information from the aircraft heading reference. In the configuration used in this project, the Singer Doppler provided the PMS with the groundspeed and drift angle information.

The PMS consists of three units: (1) an electronics assembly unit which receives the inputs from the Doppler and aircraft heading reference, performs mathematical computations on this information, and translates it into film position commands to drive the film position servo systems and binary coded data for the alphanumeric displays; (2) a Projected Map Display (PMD); and (3) a Navigation Control Unit (NCU). The PMD (Figure 3) provides distance to destination numerically on a light emmitting diode display and the following information graphically: present position, desired destination point, bearing, steering information, magnetic variation, wind velocity if true airspeed is available, and system operational status. The NCU (Figure 3) provides the following information alphanumerically: latitude/longitude or UTM coordinates of aircraft present position or any of ten preprogrammed checkpoints; bearing and flight time to any of ten preprogrammed checkpoints; groundspeed; and true airspeed and wind velocity if true airspeed is available. In this study, the PMD was located to the left of the instrument panel, directly in front of the copilot/navigator. The NCU was located adjacent to the Doppler on the center pedestal console between the two pilots.

FIGURE 3. Projected Map Display (left) and Navigation Control Unit (right) of the Projected Map System

The PMD contains a filmstrip of topographic maps which is rear projected onto the viewing screen. Present position of the aircraft or the position of any one of ten preprogrammed destinations is indicated by a circle in the center of the viewing screen. As an alternative, the copilot can choose to have present position depicted by an inverted "V" at the bottom of the screen. The display also contains a compass card, a lubber line, and a bearing pointer. Track angle of the aircraft is indicated by the intersection of the compass card and the lubber line. The intersection of the bearing pointer with the compass card represents the magnetic bearing to a selected preprogrammed destination from the present position of the aircraft. The difference in degrees between the bearing pointer and the lubber line is the discrepancy between angle of the aircraft true track and true bearing to a destination. If the bearing pointer is aligned with the lubber line, the aircraft is following a straight-line track to the desired destination.

Other PMD features include a choice of up to three map scales (depending on how many maps of different scales were put on the filmstrip), the capability of displaying the maps in a north-up or a track-up orientation, a display dim control which allows for display viewing in bright sunlight or while wearing night vision goggles, built-in test equipment, and a fail indicator lamp. Each filmstrip also contains frames on which any information, such as checklists, emergency procedures and approach plates, could be filmed when the filmstrip is produced.

Destinations are programmed into the PMS by depressing the "HOLD" button on the PMD (see Figure 3), giving the operator control of the filmstrip drives, slewing the filmstrip with the slew control until the desired geographic position is in the center of the viewing screen, and depressing the "STORE" button on the NCU. Targets may be stored while in flight by performing the same procedure.

System updates, which adjust for differences between indicated aircraft location versus actual aircraft location, are accomplished by following a procedure similar to that for storing destinations. When a known point is overflown, the "HOLD" button is depressed. The crewmember then slews the map such that the landmark over which the "HOLD" button was depressed is in the center of the viewing screen and depresses the "FIX" button on the NCU. The point over which the update was made does not have to be in system memory. (As with the destination and target storage procedures, changes in aircraft position are continuously calculated while the procedure is being performed). Once the last procedure is completed, the filmstrip automatically moves to bring aircraft present position to the viewing screen center.

For this study, the Defense Mapping Agency Aerospace Center photographed 1:50,000 scale topographic maps of portions of the Southeastern United States to make the PMD filmstrips. These maps were identical to the hand-held, 1:50,000 scale topographic maps provided to all subjects with the exception that the PMD maps did not contain annotations of checkpoints, wire hazards, and restricted areas.

The aircraft used for the project was not equipped with a true airspeed indicator, so features of either automatic navigation system requiring true airspeed input were not available to the research participants.

Hand-Held Map System: The third navigation system in the study was the standard 1:50,000 scale hand-held topographic map produced by the Defense Mapping Agency Topographic Center. This type of map is commonly used for NOE navigation by Army helicopter aircrews. The maps used by the subjects were 24 X 34 cm portions of map sheets dry mounted on cardboard and laminated with a matted plastic covering that permitted grease pencil annotation. Wires, restricted areas, checkpoints, and the initial and release points for a given course were marked on the maps before they were laminated. The area in Southern Alabama shown on a map was approximately 200 sq km (see Figure 4).

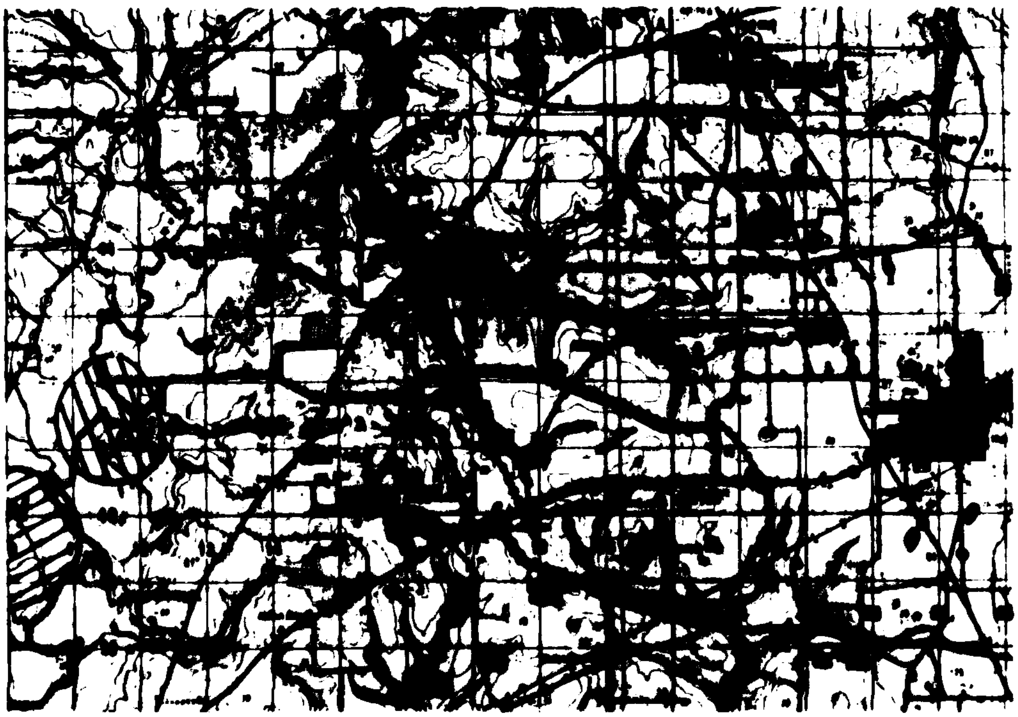

FIGURE 4. 1:50,000 Scale Hand-Held Topographic Map.

Visual Free-Time Equipment

An inactive Frequency Modulation (FM) radio control head was used in conjunction with a visual-free-time task. It was placed between the two pilots in the center pedestal console along with the other aircraft communication radios (see Figure 5). The free-time task is described in the procedure section of this report.

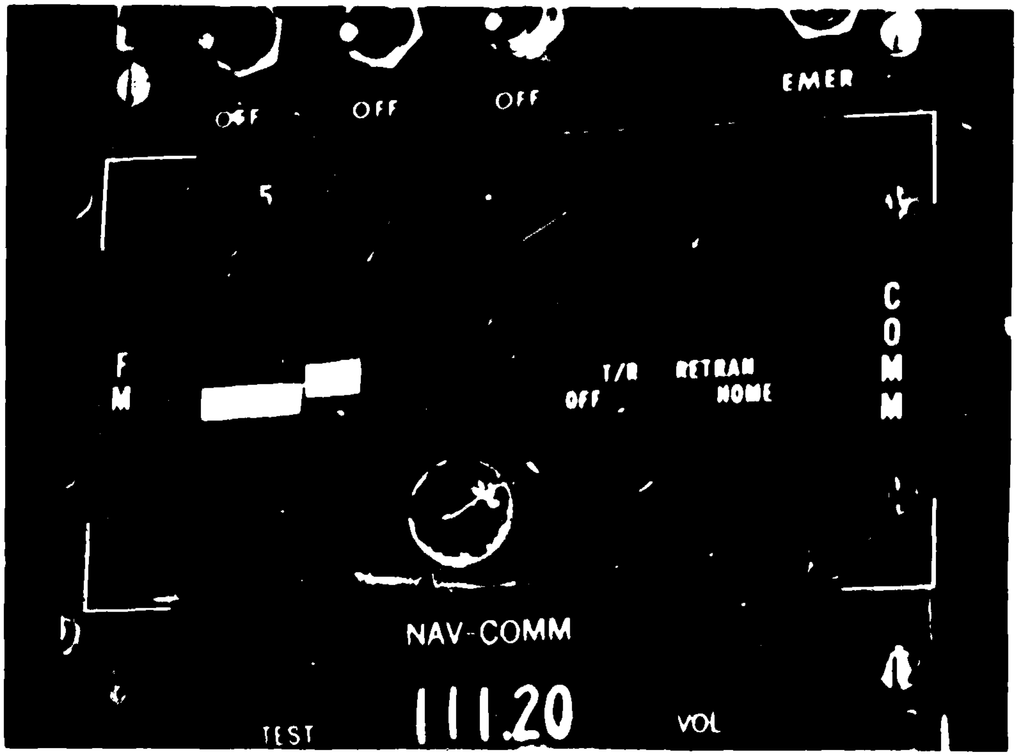

FIGURE 5. Free-Time Task Radio Control Head Located in the Center Pedestal

DATA COLLECTION EQUIPMENT

Aircraft Monitoring Equipment

A Helicopter In-Flight Monitoring System (HIMS), fabricated in-house, was used to record the flight path of the aircraft, heading, and airspeed. Its main components are an Incre-Data Corporation Mark II 7-track digital tape recorder and an Incre-Data Digital Multiplexer, Model DSM-16A. Several aircraft monitoring components and systems are interfaced with the HIMS.

The flight path of the aircraft was tracked with a Teledyne-Hastings radio ranging system, model Raydist T. The radio ranging system consists of four ground antennas, a portable navigator receiver/comparator located in the aircraft, and a fiberglass antenna mounted on the aircraft. The four ground antennas are divided into two sets, each with a continuous wave transmitter and a single sideband station. Aircraft position is determined by phase comparison of the continuous wave radio signals. Onboard the aircraft, the information is digitized and recorded by the Incre-Data digital tape recorder. The recorded position information is reduced on a laboratory computer after the test flight to yield UTM grid coordinates and pictorial plots of test flight profiles.

A Low Omni-Range Airspeed System (LORAS) manufactured by Pacer Systems, Inc., provided aircraft latitudinal and longitudinal vector velocities. All were recorded on the digital tape recorder.

Heading information was obtained from the aircraft gyromagnetic compass and recorded on the digital recorder. A complete description of the HIMS can be found in Huffman, Hofmann, and Sleeter (1972).

Eye Movement Tracking and Recording Equipment

A NAC Eye Mark Recorder and a Photo-Sonic high speed motion picture camera were used to record the copilot/navigator's eye movements on high speed film (see Figure 6). Where the subject looked was recorded using a corneal reflection eye tracking technique. A V-shaped spot of light was reflected off the cornea of the copilot's eye and superimposed on a real-time film of the scene viewed. The resultant V-shaped image on the developed film indicated the subject's visual point-of-regard. Simmons (1979) provides a thorough description of the eye movement tracking and recording equipment.

FIGURE 6. Eye NAC Eye Movement Camera on Copilot's Head.

Communications Recorder

Communications between the pilot and the copilot were recorded using a battery powered Bell and Howell 3181A audio tape recorder. The recorder was connected in parallel with the aircraft inter-communication system to yield a record of all intra-cockpit communications for post-flight analysis.

NOE FLIGHT COURSES

Three NOE courses approved for flight safety were used for the test flights. Each course was approximately 20 km in length and all were located within a 100 sq km area near Fort Rucker in Southeastern Alabama. The elevation of the area ranges from 30 to 90 m above sea level. Water features in the area include one river, several small ponds, and numerous streams. Approximately one-half of the terrain is open fields and approximately one-half is covered with vegetation. Photographs of the 1:50,000 scale topographic maps depicting the area are in Appendix B.

METHOD

SUBJECTS

Eighteen Army rotary wing aviators participated in the study. All were male volunteers (median age = 25 years) and recent graduates of the US Army Aviation Initial Entry Rotary Wing Flight Program. Each had logged approximately 175 flight hours, of which 30 hours were terrain flight navigation training, prior to participating in the research project.

EXPERIMENTAL DESIGN

The experimental design used was a randomized block design with replications (Cochran and Cox 1957). Each subject flew as copilot/navigator in one data collection flight while using only one of the three navigation systems (the hand-held map, the LDNS in conjuction with the hand-held map, or PMS with the hand-held map) on one of the three different NOE courses. Subjects were blocked by courses, so each of the three courses was flown by a total of six subjects: two subjects with the hand-held map, two with the LDNS, and two with the PMS.

PROCEDURE

Selection

One month prior to graduation of an Initial Entry Rotary Wing Flight Program class, one of the project experimenters described the research project to the class of students at the US Army Aviation Center. After the presentation the class was solicited for volunteers to serve as subjects for the research project. Once a prospective subject volunteered, an attempt was made to fit him with the NAC Eye Mark Recorder facial mask. After identifying useable volunteers (based on whether or not the facial mask fit them), post-graduation dates were set for training and participation in the project.

Training

All subjects received two hours of classroom training on the function and operations of the Doppler and the projected map systems. After this training session, subjects were assigned to one of the three navigation system conditions: the hand-held map, the Doppler, or the Projected Map System. At times one or more of the systems was not operational in a given training/test week, so strict randomness of subject assignment to navigation system conditions was modified to match the availability of equipment.

Following classroom training, subjects were brought to the research aircraft which was in a static condition on the ground and once again shown how to operate the systems with electrical power applied. Subjects operated the system they would be using in the data collection flights. This training phase usually took about one to one and a half hours for a group of three or four subjects.

After ground training, subjects were given an in-flight training session with the navigation system they would use the following day in the test/data collection sessions. They practiced navigating with the system by using it to direct the pilot over preselected courses about 50 km away from the course area to be used in the data collection flights. These practice navigation flights were at altitudes from 500 to 1000 feet above the ground. A subject was allowed to fly with a system until, in the judgment of an onboard experimenter, he was competent with it. In most cases, that took approximately 20 to 25 minutes of in-flight training.

Navigation Task

Subjects assembled at the laboratory on the day after the training sessions. They were given a 1:50,000 scale topographic map of the area in which they were to navigate. The map contained a distinctively marked initial point (IP), a release point (RP), and eight checkpoints labeled 1 through 8. Subjects were told to prepare a tactical NOE course that would bring them from the IP to each of the checkpoints in sequence and finally to the RP.

During the flight, subjects were to serve as the copilot, with navigation as their primary copilot duty. The copilot was to have the pilot maintain the helicopter in a tactical NOE profile at airspeeds the copilot deemed appropriate and direct the pilot to each of the eight checkpoints and the release point.

The research pilot played only a minimal part in the navigation of the course. The copilot/subject was instructed to give all directions to the pilot and to clearly identify each checkpoint as it was approached.

Visual-Free-Time-Task

A visual-free-time (VFT) task was devised to get an indication of the available visual free time of the copilot/subject. This was time during which the subject felt he was caught up on his navigation duties as well as his copilot duties and did not feel compelled to be looking at his map, the terrain or the aircraft instrument panel.

Subjects were given a card containing nine sets of 4-digit radio frequencies (see Figure 7). Each set contained ten frequencies and was labeled to correspond to course segments between checkpoints (e.g., 2 to 3). Subjects were told that the frequencies were those of simulated friendly ground troop units between the checkpoints and that if they had the time, they should inform the units that they were passing through the area. A unit was contacted by turning the FM radio control knob from "transmit" to "set", dialing the unit frequency, and turning the control knob back to "transmit". A red light on the face of the radio was activated to provide visual feedback whenever the radio control was in the "set" mode. Subjects were told that the procedure would simulate sending the aircraft identification and tail number to the selected ground units. Emphasis was placed on performing this task only if sufficient free time was available and that other copilot/navigator duties should not be neglected in favor of notifying ground units.

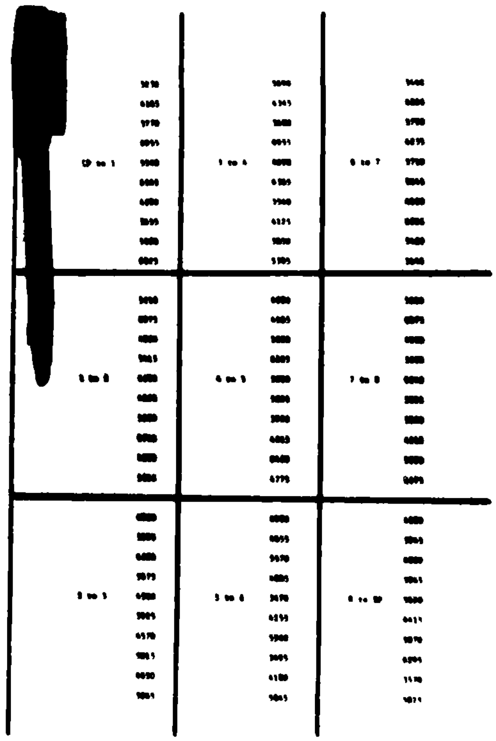

FIGURE 7. Radio Frequency Card for the Visual-Free-Time task.

Conduct of Test Flights

The subjects were flown to a laboratory stagefield near the test area. Subjects had not previously navigated in the test area.

Once at the stagefield, the NAC Eye Mark Recorder facial mask was placed on a subject and calibrated. While the subject was being fitted, an experimenter programmed the appropriate automatic navigation system the subject was to use: the Doppler or the Projected Map System. This was done to insure all checkpoints were identically programmed, thus preventing subject initiated programming mistakes which would have confounded the interpretation of the comparative data.

After the subject was ready, he took his position in the left-front copilot seat. The pilot hovered the aircraft for about one minute and then the Eye Mark Recorder was checked again for proper calibration to insure that aircraft vibration did not affect the system. If an automatic navigation system was being used, the onboard experimenter and the subject reviewed the experimenter programmed checkpoints to assure the subject that the programmed checkpoints corresponded with the checkpoints on his hand-held map. These subjects were also given the opportunity to review or practice any Doppler or PMS control functions.

For all subjects, the radio communication channels with the outside world were turned off to prevent distraction. Their communication was limited to conversation with the pilot over the intercommunication system.

After all equipment was calibrated, the laboratory pilot brought the subject/copilot to the IP of the NOE course the subject was to negotiate. From this point, the subject assumed full copilot responsibilities to include all navigation duties, assisting the pilot in hazard and obstacle avoidance, and monitoring the instrument panel. At each checkpoint, the pilot hovered the aircraft for a few seconds to allow the two-man data collection team in the rear of the aircraft to place event marks on the data tapes. The same laboratory research pilot was used for all test flights.

For safety reasons the helicopter was flown over, rather than under, power lines on the flight courses. When the aircraft flew over power lines that were higher than tree top level, the copilot/navigator subjects were prevented from obtaining a good view of the terrain by having them focus their attention on a mathematical addition task. When approaching a high tension power line, subjects were given a series of addition problems on paper. There was one problem on each piece of paper. Subjects were assured that the pilot would continue flying the helicopter in the direction they had instructed him to fly. Subjects answered the addition problems verbally until notified by the experimenter onboard the aircraft that they had passed over the power lines and were once again down at an NOE altitude.

Once on each flight an intentional attempt was made to disorient the copilot and to get him lost to determine how well the subjects could navigate from unknown locations with their respective navigation systems. The subject was required to solve a set of arithmetic problems and told that the pilot would continue flying the outlined course while the arithmetic task was being accomplished. However, while the copilot worked on his arithmetic, the pilot intentionally flew the helicopter off course. Then the copilot was allowed to return to his navigation duties and he was required to direct the pilot back to the correct course. This attempt to disorient the copilot occurred after all wires had been crossed on a course and at the same geographic location on each course.

DATA COLLECTION AND ANALYSIS

Four types of data were collected: (1) navigation performance measures, (2) communication measures, (3) eye movement measures, and (4) visual free time indicators.

Navigation Performance Measures

Navigation performance was judged by comparing several sets of recorded measures. First, an acetate copy of a subject's planned route was made from the hand-held map on which the subject had drawn his intended course. This intended course was then compared to two recordings of his actual flight path.

One recording of actual flight path came from an experimenter who was onboard the helicopter for all test flights. The experimenter, who was familiar with the test area, made notes on the subject's navigation of the course. After the flight, the subject/copilot, the pilot, and the onboard experimenter held a debriefing session in which they discussed the conduct of the flight. The acetate copy of the subject's intended route was overlayed on a map and the three individuals added a trace of what they believed to be the actual flight path flown. In the debriefing, the subject was also allowed to explain any deviations from the course he planned prior to the flight since he might have changed his plans in flight when he saw the actual terrain on the course.

The second recording of actual flight path was tracked with the Teledyne-Hastings-Raydist radio ranging system and recoded in digital form by the HIMS. These data were then plotted to yield measures of the helicopter flight path. Navigation performance was then scored from the intended flight path tracing and the two plots of actual flight path.

Other navigation performance measures collected or derived included distance flown, mean airspeed, and mean time to complete the course. Distance flown was obtained by tracing a 1:50,000 scale drawing of the actual path flown with a cartographer's map wheel. Airspeed was collected by the HIMS and a mean airspeed was calculated from the data. Time to complete the course was calculated by subtracting the time at which the aircraft departed the initial point from the time at which the aircraft arrived at the release point.

Navigation "errors" or "delays" were classifed in four categories: (1) "stops," (2) "retracks," (3) "deviations," and (4) "false identifications." The category labeled "stops" included three classes of stops: (a) the copilot/navigator telling the pilot to stop the helicopter to regain his orientation, and then continuing; (b) the copilot halting the forward progress of the helicopter and requesting the pilot to fly in a circle in the immediate area so that he could visually determine his location, and (c) the copilot requesting the pilot to stop the helicopter and perform a tactical pop-up maneuver (going above the treetop level for less than 10 seconds) so that the copilot could confirm his position.

A "retrack" was a maneuver which usually occurred when the copilot could not determine where he was. He would request the pilot to make a 180 degree turn and to follow the flight path back toward his last known checkpoint, or until he found a point he could identify. A course "deviation" was counted when a subject unintentionally strayed from his intended flight path, eventually recognized that he was off course, and directed the pilot back on course. A "false identification" was the incorrect identification of a checkpoint or release point.

Each delay was counted in only one category of delays. For example, a "false identification" could as easily be counted as a "deviation," but such errors were counted only in the "false identification" category. In order for a delay to be classified as a "stop," the subject had to be on his intended flight path. If a subject committed a deviation, stopped and determined his location, and returned to his intended path, then a "deviation" was recorded.

Communication Measures

Verbal communication between the pilot and the copilot was recorded on magnetic tape and subsequently monitored in the laboratory for analysis. Measures included the number of messages generated by the copilot and by the pilot, the average length of time spent communicating a message, the mean number of messages exchanged per minute, and the total time spent communicating during each flight. Formulas for the derivation of these measures are listed in Appendix C.

A message began when either the pilot or the copilot began to speak to the other. A message ended when the speaker stopped talking. If after a pause in speech the speaker began talking again, he was credited with having initiated another message. If after a pause the second crewmember spoke up, or if the speaker stopped talking because he was interrupted by the second, the message of the first speaker was ended and the initiation of a new message was recognized for the second speaker. Simultaneous overlapping messages by two people talking at the same time, although seldom encountered, were counted as separate messages.

The determination of the end of a message and the beginning of another was a judgmental call on the part of an experimenter and a data reduction assistant. Voice inflections, intonations, and the duration of speech pauses were key determiners in judging the beginning and the end of messages. By this scheme, a message could be a word, a group of words, a complete sentence or question, or several sentences or questions. Message duration was timed by using a stop watch while listening to the recordings.

Eye Movement Measures

Due to limited camera film capacity and the extensive amount of time required for film scoring, eye movement data were film recorded for each subject between only five pairs of checkpoints. This procedure was not known to the subjects, as they were led to believe the motion picture camera would be on for the duration of the flight. On a particular course, the checkpoints between which the motion picture camera was turned on were the same for all subjects who navigated that course. The films provided a record of approximately 15 minutes of eye movement data for each subject. Years of prior laboratory eye movement research have validated this procedure as resulting in useable measures of visual workload.

The films were developed and then viewed using a variable rate movie projector. The subject was credited with a visual "observation" each time he directed his eyes at one of seven locations: (1) outside the cockpit, (2) the hand-held map, (3) the instrument panel, (4) the free-time task, (5) the LDNS Computer Display Unit, (6) the PMS Projected Map Display, or (7) the PMS Navigation Control Unit.

For this research, an "observation" was any directing of the eyes to a particular location for a scoreable duration of time (roughly 100 msec or longer, based upon a real time film rate of 24 frames/sec and a scoring film rate of 8 frames/sec) and lasted until the film showed that the subject directed his eyes to one of the other six areas. Thus, an "observation" was not always equivalent to a fixation. For example, when a subject looked outside the left window and then shifted his gaze outside the right window, this was counted as one "observation" to the outside.

While viewing the films the film scorer entered the scoring duration of each observation into a Hewlett-Packard HP85 desktop computer by interrupting a real-time clock each time the subject shifted his visual attention to a different viewing area. Observations were categorized into areas by using a different button to interrupt the real-time clock for each area. The computer recorded the duration of each observation as indicated by the scorer, categorized the observations into the areas, and converted the scored raw data into real-time durations for each observation.

Frequency, duration, and frequency-duration values were derived from the data. Frequency computations included: (1) the total number of observations made by a subject to all areas; (2) the number of observations in each viewing area; and (3) the percentage of the total number of observations in each area. Duration calculations included: (1) the total time a subject spent making observations to the combination of all areas; (2) the cumulative duration of all observations a subject made to each area; and (3) the percentage of the total time of all observations to all areas spent in each area (2 divided by 1). Frequency-duration computations included the mean duration per observation in each area and its standard deviation and the number of observations per minute in each area. Appendix D contains the derivation of all calculations.

Visual-Free-Time-Indicators

The performance measure on the free-time task was a simple count of the visual observations of both the FM radio control and the radio frequency chart as determined in the reduction of the eye movement data. Thus, an observation of the frequency card and then an observation of the FM radio control was scored as one observation. Accuracy of radio settings was not measured in the study.

RESULTS

NAVIGATION PERFORMANCE

The results of the two-way analyses of variance (ANOVA) performed on the airspeed, time to complete the course, and distance flown data are summarized in Table 1. The mean airspeed figures in Table 1 and the individual airspeed scores subjected to the ANOVA are representative of mean aircraft airspeed over the entire course, including the short time spent in hovers at each checkpoint dictated by experimental procedures. Airspeed was the only navigation performance measure subjected to statistical analysis that was significantly affected by navigation systems. Duncan's (1955) multiple range test revealed that the mean airspeed of the HHM group was significantly slower than that of the LDNS group ($p < .05$) and the PMS group ($p < .05$). Appendix E contains a complete summary of the navigation performance data and Appendix F contains the complete ANOVA summary tables for the navigation data.

TABLE 1

NAVIGATION PERFORMANCE MEASURES

PERFORMANCE MEASURES	MEAN[+] (STANDARD DEVIATION)			F	P
	Navigation System[++]				
	HHM	LDNS	PMS		
Mean Airspeed (kn)	26[a*] (3)	34 (3)	33 (6)	8.94	0.004
Mean Flight Time (min)	33[a] (6)	28[a] (7)	27[a] (5)	2.35	0.134
Mean Distance Flown (km)	26[a] (6)	27[a] (7)	24[a] (5)	1.21	0.236

+ n=6

++ HHM : Hand-Held Map
LDNS: Lightweight Doppler Navigation System
PMS : Projected Map System

* Mean values with a common superscript are not significantly different from each other at $p = 0.05$.

The navigation delay data are listed by type in Table 2. Overall, the Hand-Held Map (HHM) group committed the most delays (14) and the Projected Map System (PMS) group generated the least number of delays (5). At least one navigation delay occurred on four of the six HHM flights and on five of the six LDNS flights. Three of the six PMS subjects made at least one navigation delay.

TABLE 2

FREQUENCY OF NAVIGATION DELAYS

DELAY	NAVIGATION SYSTEM		
	HHM	LDNS	PMS
False Identification	6	1	3 *
Deviation	0	5	2
Retrack	2	0	0
Stop	6	3	0
TOTAL	14 **	9	5

* Made by the same subject

** Three false identifications and two stops made by the same subject.

Median vector error for deviations and false identifications (Table 3) was smallest for the LDNS group (560 m with a range of 320 to 940 m, n = 6) and greatest for the HHM group (1050 m with a range of 340 to 1940 m, n = 6). The PMS group had a median vector error of 970 m (range of 200 to 1480 m, n = 5). These PMS values result from three false identifications and two deviations (Table 2). The three false identifications were made by the same subject. This copilot had convinced himself that he was somewhere on the map other than at his actual location (displayed by the PMS) and thus did not believe the PMS was functioning properly. During this time, the individual did not appear to use the PMS for navigation purposes, but he did check the system frequently. The individual incorrectly identified three successive checkpoints, making errors of 970 m, 1310 m, and 1480 m before realizing he was disoriented and the PMS was displaying correct aircraft position. The other two PMS group delays (deviations of 200 m and 900 m) were committed by two different subjects.

TABLE 3

FALSE IDENTIFICATION AND DEVIATION MAGNITUDES

ERROR	NAVIGATION SYSTEM		
	HHM (n=6)	LDNS (n=6)	PMS (n=6)
Mean Vector Error (m) *	1020 (572) **	620 (224)	970 (490)
Median Vector Error (m)	1050	560	970
Vector Error Range (m)	340-1940	320-940	200-1480

* Rounded to nearest 10 m.

** Standard deviation of mean vector error.

None of the reported data in Tables 2 and 3 include the attempted disorientation (see procedures section) in which the pilot intentionally flew the aircraft off course while the copilot was doing an arithmetic task designed to distract him. Once they finished with the arithmetic task and looked outside the aircraft, all subjects realized they were off course and readily directed the pilot back to their desired flight path.

COMMUNICATION WORKLOAD

The communication workload data are summarized in Table 4. Although there were no significant main effects due to navigation systems, a post hoc Duncan's test on the mean number of messages per flight by the three groups revealed that the mean number of messages per flight for the HHM group (121 messages per flight) was significantly greater than that of the LDNS group (91 messages per flight) ($p < .05$). Appendix G contains a detailed summary of the communication data and Appendix H contains the ANOVA summary tables.

TABLE 4

COMMUNICATION WORKLOAD MEASURES

COMMUNICATION WORKLOAD MEASURES	MEAN*				
	Navigation System				
	HHM	LDNS	PMS	F	p
1. Messages/Flight	121[a**]	91[b]	100[ab]	3.19	0.075
2. Messages/Minute	3.7[a]	3.2[a]	3.8[a]	1.11	0.359
3. Time/Message (sec)	4.1[a]	3.8[a]	4.5[a]	0.87	0.441
4. Time/Flight in navigation communication (min)	8.2[a]	5.8[a]	7.1[a]	2.12	0.159
5. Proportion of flight time in navigation communication	.245	.207	.268	2.22	0.148

* n = 6

** Mean values with a common superscript are not significantly different from each other at p = 0.05.

VISUAL WORKLOAD

A summary of the eye movement data is presented in Tables 5, 6, and 7. For each of the three groups, Table 5 contains the proportion of all observations directed to each of the seven areas. That is, as the first line depicts, the six subjects who used the HHM directed an average of 46% of their total number of recorded observations to area 1 (outside the helicopter). Subjects who used the LDNS directed 44% of their observations outside the helicopter, and subjects who used the PMS directed 39% of their observations outside the helicopter.

TABLE 5

EYE MOVEMENT OBSERVATION FREQUENCIES

VIEWING AREA	MEAN PROPORTION OF OBSERVATIONS SPENT IN EACH AREA		
	Navigation system		
	HHM	LDNS	PMS
*			
1	.46	.44	.39
2	.44	.34	.36
3	.08	.15	.09
4	.02	.03	.03
5		.03	
6			.11
7			.01

*

AREAS
1. Outside the Helicopter
2. Hand-Held Map
3. Instrument Panel
4. Free-Time Task
5. LDNS Computer-Display Unit
6. PMS Projected Map Display
7. PMS Navigation Control Unit

The proportions of the total time spent viewing each of the areas are listed in Table 6. The data for area 1 indicated that the HHM and LDNS groups spent an average of 49% of their recorded observation time looking outside the helicopter while the PMS group spent an average of 59% of their observation time looking outside the helicopter.

TABLE 6

EYE MOVEMENT TIME DATA

VIEWING AREA	MEAN PROPORTION OF TIME SPENT IN EACH AREA		
	Navigation system		
	HHM	LDNS	PMS
*			
1	.49	.49	.59
2	.39	.31	.22
3	.04	.09	.04
4	.08	.10	.06
5		.02	
6			.07
7			.01

*

AREAS
1. Outside the Helicopter
2. Hand-Held Map
3. Instrument Panel
4. Free-Time Task
5. LDNS Computer-Display Unit
6. PMS Projected Map Display
7. PMS Navigation Control Unit

The left side of Table 7 contains the mean duration of observations in each area for the three groups of subjects. These values were obtained by dividing each subject's total viewing time in an area by his number of observations to that area and then taking the mean of the resulting six values. Thus, the first line of the left side of Table 7 indicates that: (1) the HHM group spent a mean time of 3.0 s per observation outside the helicopter (area 1), (2) the LDNS group had a mean time per observation outside the helicopter of 2.5 s and (3) the PMS group devoted an average of 5.5 s per observation outside the helicopter.

The mean number of observations per minute to each area is contained on the right side of Table 7. Thus, area 1 was observed, on the average, 10.2 times per minute by the subjects using the HHM as their navigation system. Similarly, the LDNS subjects looked outside the cockpit an average of 12.2 times per minute and the group navigating with the PMS had a mean number of 6.7 observations per minute outside the cockpit.

TABLE 7

EYE MOVEMENT TIME-FREQUENCY DATA SUMMARY

* AREA	TIME PER OBSERVATION (in seconds)			OBSERVATIONS PER MINUTE (mean)		
	Navigation System			Navigation System		
	HHM	LDNS	PMS	HHM	LDNS	PMS
1.	3.0	2.5	5.5	10.2	12.2	6.7
2.	2.4	2.0	2.1	10.0	9.6	6.3
3.	1.5	1.2	1.6	1.7	3.6	1.7
4.	10.7	6.7	9.4	0.4	0.9	0.5
5.		1.6			0.7	
6.			2.0			2.1
7.			1.5			0.1

*
AREAS
1. Outside the Helicopter
2. Hand-Held Map
3. Instrument Panel
4. Free-Time Task
5. LDNS Computer-Display Unit
6. PMS Projected Map Display
7. PMS Navigation Control Unit

The results of the visual workload analyses are presented in Table 8. The complete ANOVA summary tables for the results listed in Table 8 are contained in Appendix I and the individual data that were combined to construct Table 8 are in Appendix J.

TABLE 8

VISUAL WORKLOAD MEASURES

VISUAL WORKLOAD VARIABLES	MEAN*			F	p
	Navigation System				
	HHM	LDNS	PMS		
1. Overall number of observations/min	22.3^{ab**}	28.0^{a}	17.4^{b}	6.83	0.009
2. Observations/min outside	10.2^{a}	12.2^{a}	6.7^{b}	12.84	< 0.001
3. Observations/min on navigation system	10.0^{a}	10.8^{a}	8.6^{a}	1.40	0.281
4. Proportion of observations outside	$.46^{a}$	$.44^{a}$	$.39^{b}$	34.93	< 0.001
5. Proportion of time on navigation system	$.38^{a}$	$.31^{a}$	$.28^{a}$	2.13	0.159
6. Proportion of time outside	$.49^{a}$	$.49^{a}$	$.59^{b}$	4.76	0.028
7. Proportion of time navigating	$.88^{a}$	$.81^{b}$	$.89^{a}$	5.76	0.016
8. Mean time/observation outside	3.0^{a}	2.5^{a}	5.5^{b}	16.51	< 0.001

* n = 6

** Mean values with a common superscript are not significantly different from each other at $p = 0.05$.

Observations Outside the Cockpit

Subjects who used the PMS devoted a significanty smaller ($p < 0.05$) proportion (.39) of their observations outside the cockpit (area 1) than either of the other two groups (variable 4, Table 8). The PMS group also devoted a significantly greater ($p < 0.05$) proportion of their viewing time outside (variable 6, Table 8) and made significantly fewer ($p < 0.05$) observations per minute outside the helicopter than the LDNS and the HHM groups (variable 2, table 8). It follows that the PMS group's mean time per observation outside was significantly longer ($p < 0.05$) than either of the other two groups (variable 8, Table 8).

Observations Toward Navigation Systems

Summing the eye movement time data (Table 6) for select visual areas yields a measure of the total proportion of time a group spent viewing their particular navigation system. That is, combining the time values of the PMS subjects for areas 2, 6, and 7 yields the aggregate proportion of time they spent viewing the three components comprising their navigation system: HHM, PMD, and NCU. Likewise, combining the LDNS subjects' proportion of time on areas 2 and 5 yields the cumulative proportion of time spent viewing their navigation system: HHM and CDU. The HHM subjects' navigation system consisted only of the HHM itself (visual area 2). These combined values are presented as variable 5 in Table 8.

A shortcoming of this grouping is the exclusion of copilot's observation of the Radio Magnetic Indicator (RMI) on the instrument panel. Aircraft heading is an important piece of navigation information obtained from the RMI, but the scoring procedures used in this study counted an observation anywhere on the instrument panel as an observation to visual area 3 and did not differentiate glances to the RMI as such. Thus, the observation data for navigation systems (variable 5 in Table 8) may be incomplete to the extent that some subjects may have occasionally glanced at the RMI for heading information and it was not counted in this measure. This may be more pronounced in the case of the LDNS subjects who devoted, on the average, 16% of their observations to the instrument panel (Table 5).

However, considering the navigation systems as defined above, the proportion of total visual time spent by the groups on their navigation systems was not significantly different. Even when common proportion transformations were used ($\ln x$, $\ln (x/1-x)$, and the arc sine of the square root of x), no significant differences were found. The number of observations per minute (variable 3, Table 8) on their respective navigation systems also was not significantly different. The inverse and the natural log transformations of these rate data also failed to yield a significant difference.

Visual Workload on Navigation Task

The total visual time a subject devoted to the task of navigation can be inferred by adding the proportions of time spent looking outside the cockpit (variable 6, Table 8) and the time spent looking at the respective navigation components (variable 5, Table 8). The resultant proportion of time spent navigating is variable 7 in Table 8. The analysis of this variable revealed that the LDNS group spent a smaller ($p < 0.05$) proportion of their visual time navigating than the HHM group and the PMS group. As was pointed out above, it is likely that some of the time spent looking at the instrument panel (area 3) was directed to the RMI. Thus, the figures for the proportion of total visual time spent navigating (variable 7, table 8) might be slightly higher for one or more groups of subjects if glances at the RMI are considered.

Visual Activity

The overall number of observations per minute (frequency of observations toward all areas) indicates how rapidly subjects changed their point-of-regard, or, their visual activity (variable 1, Table 8). The PMS group's visual activity was less than that of the LDNS group ($p < 0.05$). Differences between the HHM and the other two groups were not significant.

VISUAL FREE TIME

The proportions of observations spent by the three groups looking at the visual free-time task (FM radio control and frequency chart; area 4, Table 5) were very low and similar: only 2 to 3% of all the recorded observations. For the LDNS group, the observation rate of 0.9 observations per minute (column 2, Table 7) on the task, although low, was close to twice the rate for either the HHM or the PMS groups (0.4/min and 0.5/min, respectively).

It is not clear from these data why the LDNS group had a tendency to look at the free-time task more often than the HHM and PMS groups. It might be that the LDNS provided subjects with more free time to look at the task more frequently, or the positioning of the FM radio close to the LDNS CDU may have resulted in a tendency of subjects to look at both in successive glances.

Because of the low frequency of observations to the free-time task and possible confounding effects due to the location of the free-time task radio control head as described above, these data were not statistically tested.

DISCUSSION

NAVIGATION PERFORMANCE

The navigation performance data from this project are compatible with those collected in several different studies. Barnard and others (1976) and Weseman (1977) found that aircrews who used a hand-held map became disoriented on at least 50% of their flights. In the study presented here, four of six subjects became disoriented while using a hand-held map.

Lewis and Anderson (1969), in a study comparing a projected map display to a hand-held map, and McKechnie (1970), in a study comparing a roller map display to a hand-held map, observed that the largest navigation errors were made by the hand-held map subjects. In the study described in this report, the subjects using the hand-held map had the largest mean vector error for deviations and false identifications.

It is very difficult to interpret course error data on a practical basis because in performing a navigation task the acceptability of any degree of "error" is situation dependent. The utility helicopter NOE navigation training requirements specify that the aircrew will know their location within 100m, 100% of the time (Department of the Army 1979). If one uses these criteria, then every error detected and scored in this project would be considered a navigation error (see Appendix E for individual vector error values).

Associated with every disorientation is the problem of the aircrew getting back to the desired route. First, the crew must establish were they are in relation to their intended track. If they suddenly realize they are not where they thought they were, but then determine their location from their immediate surroundings, they can quickly establish a course of action and return to their desired flight path. However, if they cannot determine where they are (a common occurrence at NOE altitudes), they must orient themselves using one or more of the techniques discussed below.

To get reoriented, the aircrew can attempt to retrack the path they flew that led them to their unknown location; they can follow a line feature or maintain a specific heading until an identifiable landmark is found; or they can fly above NOE altitudes and look for terrain features they can identify on the map. However, all of these choices can be risky in a tactical situation when the aircrew does not know their location relative to potential enemy threats.

Having an automatic navigation system, the aircrew can maintain their NOE status, immediately determine their position, and choose the route that they believe would most safely return them to their desired flight path.

Another advantage to having an automatic navigation system is the aid it provides the aircrew in determining when they are off course. Oftentimes, a navigator will force-fit the terrain and the intended location on the map, getting further off-track, until eventually there is no similarity between where he thinks they are on the map and their actual position. From the magnitudes of deviations and false identifications in this study (mean vector error: HHM = 1020 m; LDNS = 560 m; PMS = 970 m) and the results reported by others (McKechnie 1970, Lewis and Anderson 1969) it is apparent that aircrews with an automatic navigation system do not continue force-fitting as long as aircrews with only a hand-held map, and thus do not travel as far from their intended path before they realize they are disoriented.

The frequency of navigation delays made by the three groups of subjects further supports the above discussion. On six occasions the HHM subjects were unaware they were off-track and incorrectly identified a checkpoint. Two HHM subjects also had to retrack their flight path from an unknown location in order to reorient. Thus, out of eight HHM deviations from intended course, only two deviations were detected and corrected. However, of the eleven deviations by the two automatic navigation system groups, the copilots recovered from seven of the deviations. (Three of the four unrecovered deviations were false identifications committed by a PMS subject who did not believe the PMS was functioning properly.)

Due to the relatively greater number of navigation delays experienced by the HHM group as opposed to the automatic navigation groups, it is difficult to interpret the significant difference ($p < 0.05$) between the HHM group's mean airspeed (25.8 km/h) and the airspeed of the LDNS and PMS groups (33.6 km/h and 32.5 km/h, respectively). It may be that the slower airspeed of an aircrew using a HHM is simply a reflection of their greater number of delays such as stops, diorientations, and incorrect checkpoint identifications. Nevertheless, the data indicate that navigators with automatic navigation systems will get to a destination faster and with fewer deviations from their intended flight path.

COMMUNICATION WORKLOAD

The only significant effect found in the analyses of the communication data was a simple effect of messages. Fewer ($p < 0.05$) navigation messages were spoken per flight (91) by the LDNS pilot/copilot teams than by the HHM teams (121). Although analyses of variance on the data did not identify any statistically significant navigation system main effects due to navigation systems, analyses of covariance using covariates of windspeed and temperature and some transformations of these two covariates and the dependent variables often produced statistical probability values (p) in the 0.06 to 0.15 range.

Although no significant navigation system main effects were obtained between groups, the data does expose some interesting information concerning navigation communication. The pilot/copilot teams generated an average of more than three messages per minute (Table 4, row 2), or, put another way, they spoke to each other at least every 20 seconds. Another interesting statistic is the mean proportion of flight time spent in navigation communication (Table 4, row 5). The HHM group spent an average of 8.2 minutes per 32.9 minute flight or 25% of their flight time in navigation conversation. The LDNS subjects spent an average of 5.8 minutes per 27.6 minute flight for 21% of their flight time in navigation conversation, and the PMS group spent an average of 7.1 minutes of a 26.7 minute flight or 27% of their time in navigation communication.

These results are compatible with the findings of Sanders and others (1975) who objectively measured the percent of flight time spent in communication by student pilot-copilot teams while flying NOE with a hand-held map. From objective and subjective data, they concluded that pilot/copilot teams who have flown together for some time spend less flight time in navigation communication than teams that have flown together for only a short time. Subjective pilot responses indicated that this difference was due to the more familiar teams using navigation terminology that had the same meaning to both team members. As a result, there is less need to clarify instructions as is necessary with less familiar teams.

A navigation lexicon would reduce the number of words used by navigators to convey navigation instructions. As a result, the probability of listener recognition of any communication would be increased, i.e., the pilot would not have to ask the navigator to clarify his instructions (Miller, Heise and Lichten 1951), and communication time would be reduced. DeVries and Laveson (1973) found that a standard lexicon used for communication between forward air controllers and tactical air command pilots significantly improved their performance. The mean time to locate terrain features was reduced by nearly a factor of two. Furthermore, the lexicon trained group correctly located 99% of the assigned terrain features while the control group correctly located only 66% of the assigned terrain features.

Unfortunately, student pilots are not taught a standard navigation lexicon. Valuable time is spent in communication by unfamiliar flight crews until they develop a set of mutually agreeable terms. Thus, navigation performance may be less than optimum.

In addition to the communication workload imposed by navigation tasks, the aircrew must also speak to crews in other aircraft, coordinate with air traffic controllers and forward observers, direct ground troop units, inform command posts of tactical situations, and coordinate air space with combat support units. Since much of this type of communication is tactically important and thus of interest to the enemy, it may be coded to prevent intelligible monitoring. Consequently, an even higher communication workload is imposed by these non-navigation tasks due to the necessary coding and decoding. Improvements in communication procedures and terminology for navigation and non-navigation communication tasks may reduce aircrew communication workload and improve aircrew performance.

VISUAL WORKLOAD

Observations Outside Cockpit

The proportion of visual time the HHM group spent looking outside the cockpit (.59) in this study is similar to that found by Sanders, Simmons and Hofmann (1979) and Barnard and others (1976), .57 and .50, respectively. Of the three subject groups in this study, the PMS group spent the greatest proportion of visual time looking outside (.59) and devoted the smallest proportion of observations outside (.39). They also had the smallest observation rate outside (6.7 observations per minute) and spent more time outside per observation (5.5 s) than either of the other two groups. These results have some important implications.

First, the PMS subjects were able to spend more time looking outside the aircraft with the fewest number of visual transitions. Said another way, they did the least amount of visual work and spent the greatest amount of time viewing outside the helicopter. Second, since the PMS group had the least number of observations outside per minute, they spent less of their time in a sub-maximal information gaining state which occurs during head movements, eye movements, accommodation, and brightness adaptation. It has been estimated that the transition from viewing the world outside the cockpit to viewing the instruments takes about 0.8 s (Wulfeck, Weisg, and Raben 1958, Hasselbring 1970). Third, since the PMS group spent nearly twice as much time per observation outside as the other two groups, one might assume that a larger area was observed with each outside observation. The viewing of larger areas could enable the navigator to acquire more terrain information for navigation purposes. Finally, the higher proportion of time spent looking outside by the PMS group could aid in the detection of hazards, obstacles, and targets. Gabriel (1965) found that aircrewmen who spent more time looking outside the cockpit spotted more aircraft targets. Although the greatest potential threat to helicopters may not be other aircraft, the higher visual time outside the cockpit may increase the detection rate of ground threats or targets (most often the mission of scout or attack helicopter crews).

Observations Toward Navigation System

The between group differences for the observation rate on the navigation system, the proportion of visual time on the navigation systems, and the proportion of observations on the navigation systems were not significantly different ($p > 0.05$). However, the results obtained for subjects using the HHM are similar to those of Sanders, Simmons, and Hofmann (1979). The observation rate on the hand-held map by the HHM group in this study was 10.0 observations per minute while the subjects in the Sanders and others study had an observation rate of 10.6 observations per minute. Furthermore, the HHM group in this study spent 38% of their visual time on the map and the subjects in the Sanders and others study spent 35% of their visual time on the hand-held map when flying NOE.

Some of the proportion results derived for the automatic navigation system groups may vary with more experienced users. For example, after extended use of the PMS, a copilot/navigator may increase his use of the display for topographic information as opposed to relying on the display primarily for position information and the hand-held map for topographic information.

Visual Workload on Navigation Task

The time an individual devoted to the navigation task was defined as the sum of: (1) the time he spent looking at his navigation equipment, and (2) the time he spent looking outside. The LDNS subjects spent less time navigating than either of the other two groups. The results obtained for the HHM group are similar to those obtained by Sanders, Simmons, and Hofmann (1979). The HHM group in this study spent 88% of their visual time navigating while Sanders and others found that subjects spent 91% of their time looking outside and at the hand-held map during NOE flight.

The amount of time subjects spent navigating provides some insight as to the visual time required by, or workload associated with, the task of NOE navigation. All groups spent more than 80% of their visual time navigating. The HHM and PMS groups spent nearly 90% of their time navigating. That leaves a small proportion of the copilot's time for other duties.

One may question whether all time looking outside can be credited as navigation time. However, if one looks at the short time per observation for the HHM and LDNS groups (3.0 and 2.5 s, respectively), it is clear that these subjects were not wasting any time when looking outside the helicopter. The PMS group may have had longer observations outside (5.5 s per observation) because they did not have to continuously cross-check the terrain outside with their hand-held map to keep track of their position. The map display constantly displayed their position on a map identical to the one they had in their hands. One cannot determine what these subjects did with their "extra" time looking outside, but it may have been used for hazard and obstacle detection and insuring clearance of the helicopter rotor blades from nearby tree limbs. In a combat environment, this extra time could also be used to search for potential ground threats.

Visual Activity

Visual activity was defined as the number of observations per minute. The PMS group had a slower observation rate (17.4 observations per minute) than the LDNS group (28.0 observations per minute). There was no statistically significant difference between the observation rates of the HHM group and either of the other two groups (see Table 8).

Since an observation, as we defined it in this study, could contain one or more visual fixations (see the Data Collection and Analysis section of this report), it is difficult to interpret the results of the analysis. For example, the mean duration of observations outside the helicopter by the PMS group (5.5 s) was significantly longer than the duration of observations outside the helicopter by the HHM group (3.0 s) and the LDNS group (2.5 s) ($p < 0.05$). Because the PMS group spent nearly twice the time per observation outside the helicopter than the other two groups, it is reasonable to assume that the PMS subjects were making more fixations than the HHM and the LDNS subjects each time they looked outside the helicopter. Consequently, if the overall visual activity of the three groups was measured in visual fixations per minute as opposed to observations per minute, then there may not have been a difference in visual activity between the PMS group and the LDNS group.

VISUAL FREE TIME

It is readily apparent from the free-time task data for the HHM and PMS groups (Table 6) that subjects did not have abundant free time. The observations per minute on the free-time task for the HHM group (0.4) is the same observation rate reported by Sanders, Simmons, and Hofmann (1979) on a different in-flight free-time task. In their study, the free-time task accounted for 3% of the subjects' visual time. In the present study, the free-time task accounted for a greater percentage of the HHM group's visual time (8%). The difference between the two studies in the proportion of visual time accounted for by the free-time task may partially be due to the longer time required to perform the free-time task in the present study. The data in Table 6 indicate that the LDNS group had more free time than the other two groups. However as was mentioned in the Results section, the visual-free-time data of the LDNS group may be confounded due to the close proximity of the LDNS computer-display unit and the free-time task radio control head.

As is true with the evaluation of any secondary task, it is difficult to assess whether or not subjects could have spent more time on the task without degrading their navigation performance. For example, one may ask: Could the PMS subjects have spent more time performing the free-time task without becoming disoriented as opposed to spending a larger proportion of their time looking outside the helicopter than the other two groups? Or, did the PMS subjects feel that it was necessary to spend a larger proportion of their time looking outside than the other two groups?

The PMS may have provided the PMS subjects with more free time, but they may have felt that they could improve their navigation performance by using the visual time to maintain their attention outside the cockpit. If the PMS subjects did have more free time than the other subjects, they may have also used this time to visually search for hazards and obstacles. Thus, if workload was reduced and extra visual time was provided, the extra free time may have been used on the navigation task.

If an automatic navigation system simply allows the navigator to do the job of navigation "more completely," then it is not contributing any real useable free visual time. However, if the copilot/navigator has other tasks to perform, he can perform his navigation duties with the assistance of an automatic navigation system at the same level as with a hand-held map and perform other duties as long as they do not demand more time than the extra time made available by the navigation system. Knowing his own workload level, only the copilot can make these tradeoffs.

Maybe the real advantage of automatic navigation systems is not that they provide any real extra free time, but that they prevent navigation errors from occurring, or, if they do occur, prevent them from becoming too large before they are recognized. Furthermore, if attention to the navigation task is disturbed (e.g., enemy weapons firing) and the pilot maneuvers the helicopter to an unknown location, then the systems provide the aircrew with their location and details on how to get to a specific point.

CONCLUSION

Copilot/navigator workload and performance were examined during nap-of-the-earth (NOE) flight. Copilot/navigators used one of three navigation systems: a Hand-Held Map (HHM), a Lightweight Doppler Navigation System (LDNS), or, a Projected Map System (PMS). Three types of data were collected: (1) copilot navigation performance, (2) intracrew communication workload, and (3) copilot visual workload.

In this study, as in others (Barnard and others 1976, Lewis and Anderson 1969, McKechnie 1970, Weseman 1977), it was found that: (1) disorientation occurs on a majority of low level flights when only a hand-held map is used for navigation, and (2) aircrews stray farther from their intended track when navigating with a hand-held map than they do when using an automatic navigation system and a hand-held map. Additionally, aircrews using an automatic navigation system usually fly at a higher mean airspeed and get to their destination faster. It is proposed that the reason for fewer disorientations by aircrews with an automatic navigation system is due to the fact that aircrews are alerted to deviations from their intended track through their monitoring of the system displays.

Communication data collected revealed that a large percentage of the aircrew's time is spent in navigation communication. Navigation communication time ranged from 21% to 27% of the total flight time across the three navigation systems. There were no significant differences between groups ($p > 0.05$). The pilot and copilot, on the average, provided each other with navigation information at least three times a minute. These figures do not include the communicating that the aircrew must do for tasks other than navigation such as for target acquisition, interaircraft coordination, artillery fire coordination, etc.

An analysis of the number of navigation messages per flight showed that fewer navigation messages were spoken by the Doppler pilot-subject teams than by the HHM pilot-subject teams ($p < 0.05$).

Several informative results were obtained from the visual workload data. From the analyses of the observations or looks outside the helicopter by the three groups of subjects, it was found that the PMS group spent: (1) a greater proportion of their flight time looking outside the cockpit, (2) a smaller proportion of their observations outside, and (3) a greater amount of time per observation outside the cockpit than either of the other two groups. The PMS group also made fewer observations per minute to outside the helicopter than either of the other two groups. Thus, the PMS group was able to spend more time viewing outside the helicopter with less visual activity/visual workload and spend less time in large visual transitions, glancing from inside the cockpit to outside the cockpit. Furthermore, by spending more time viewing outside, their probability of hazard, obstacle, or threat detection is assumed to increase.

Looking at the proportion of flight time spent navigating, it was found that the LDNS group spent less time navigating than either of the other two groups ($p < 0.05$). However, all groups spent more than 80% of their time navigating, indicating that even with an automatic navigation system, navigating at NOE flight altitudes is a high workload task.

A visual-free-time task was employed to determine the amount of free time available to a copilot/navigator using one of the automatic navigation systems or only the hand-held map. It is readily apparent from the data that copilot/navigators have very little visual free time during NOE flight, even when using an automatic navigation system.

The following summarizes the findings of this study:

a. Automatic navigation systems reduce the number of navigation errors committed by the copilot/navigator and reduce the size of deviations from intended track when navigation errors occur.

b. Mean airspeed is statistically significantly greater when using an automatic navigation system.

c. Navigation communication occupies more than 20% of the aircrew's time when using either a hand-held map, a Doppler, or a projected map system.

d. The copilot and pilot provide navigation information to each other at an average rate of more than three times a minute when using a hand-held map, a Doppler, or a projected map system.

e. When flying with a Doppler versus a hand-held map, significantly fewer verbal exchanges concerning navigation are made between the pilot and copilot.

f. Copilot/navigators using a projected map system spend significantly more time looking outside the helicopter than individuals with a Doppler or a hand-held map.

g. Copilot/navigators using a projected map system experience lower levels of visual activity/visual workload than individuals using a Doppler.

h. Copilot/navigators using a Doppler spend less time navigating than individuals using a projected map system or a hand-held map.

i. Copilot/navigators spend more than 80% of their visual time navigating when using either a hand-held map, a Doppler, or a projected map system.

j. Less than 10% of the copilot/navigator's visual time is "free time," time that the copilot believes that he does not have to spend on the navigation task when using either a hand-held map, a Doppler, or a projected map system.

Although not tested directly in this study, some of the most important advantages to having an automatic navigation system are inherent system features such as the capability of displaying aircraft present position or distance, bearing, and time to a selected destination. These features are extremely important when crews become disoriented or when in the immediate vicinity of enemy forces.

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Appendix A

EQUIPMENT MANUFACTURER LIST

MANUFACTURERS AND LOCATION

Bell and Howell Company
Chicago, Illinois

Computing Devices Company
Ottawa, Canada

Hewlett-Packard
Bevertown, Oregon

Incre-Data Corporation
Albuquerque, Ari.ona

Pacer Systems, Incorporated
Burlington, Massachusetts

NAC
Instrumentation Marketing Corporation
Greensboro, North Carolina

Photo-Sonics, Incorporated
Burbank, California

Singer
Kearfott Division
Wayne, N.J.

Teledyne-Hastings-Raydist
Hampton, Virginia

Teledyne-Ryan Electronics
Northridge, California

Appendix B

NAP-OF-THE-EARTH NAVIGATION COURSES

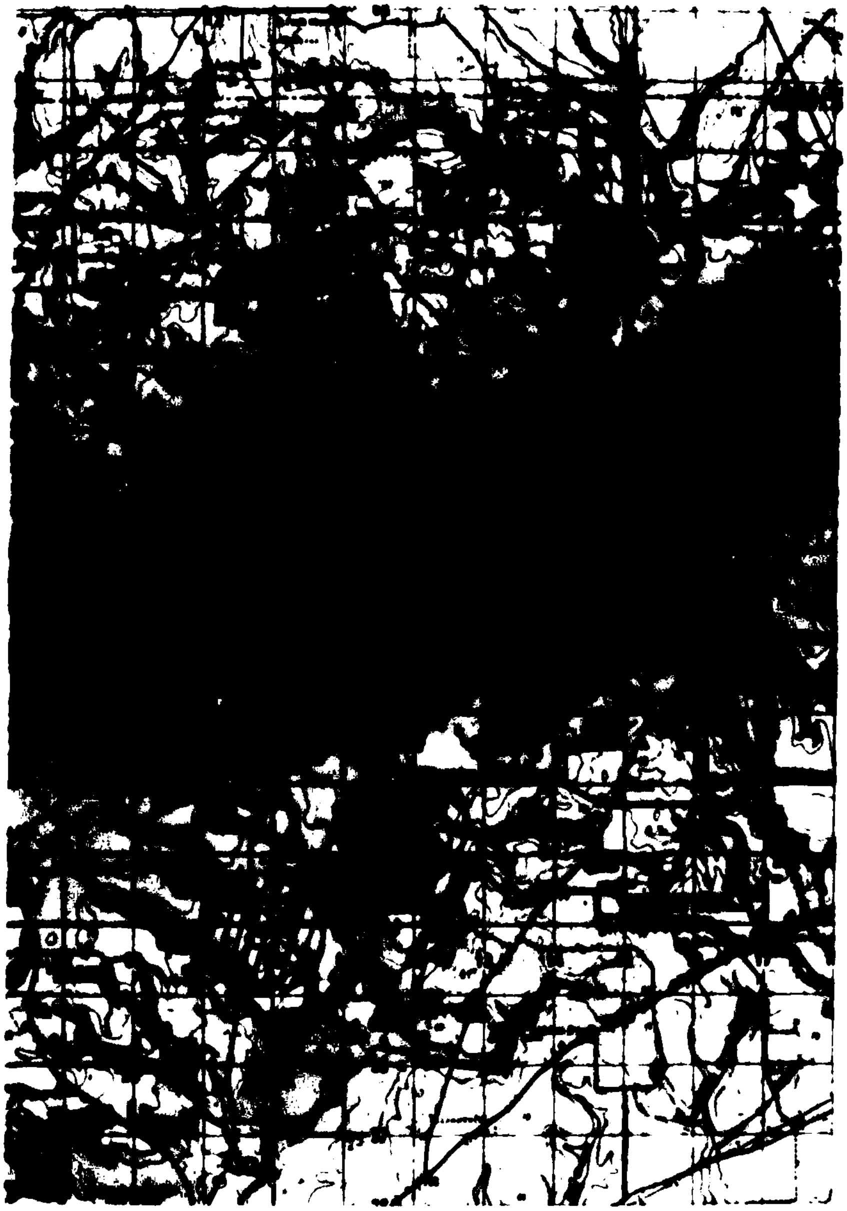

FIGURE B-1. Nap-of-the-earth navigation course no. 1.

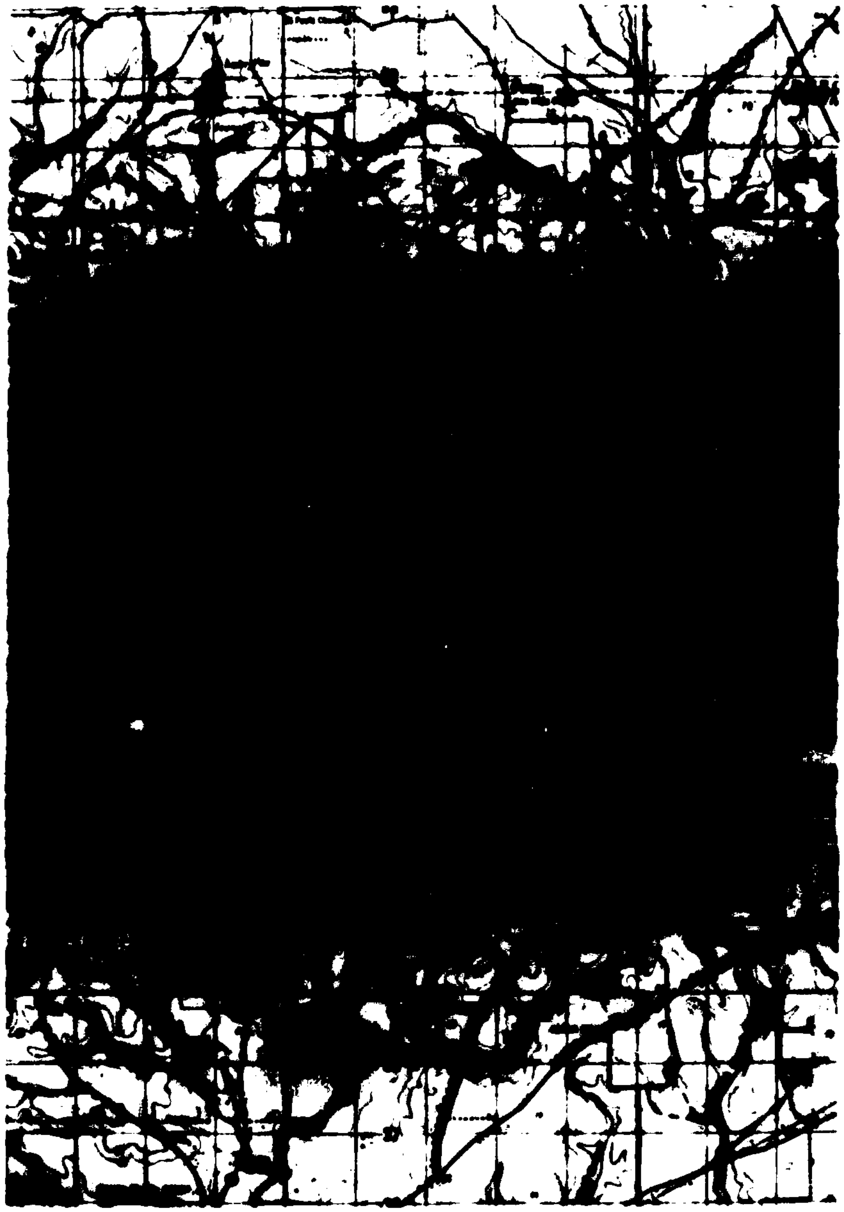

FIGURE B-2. Nap-of-the-earth navigation course no. 2.

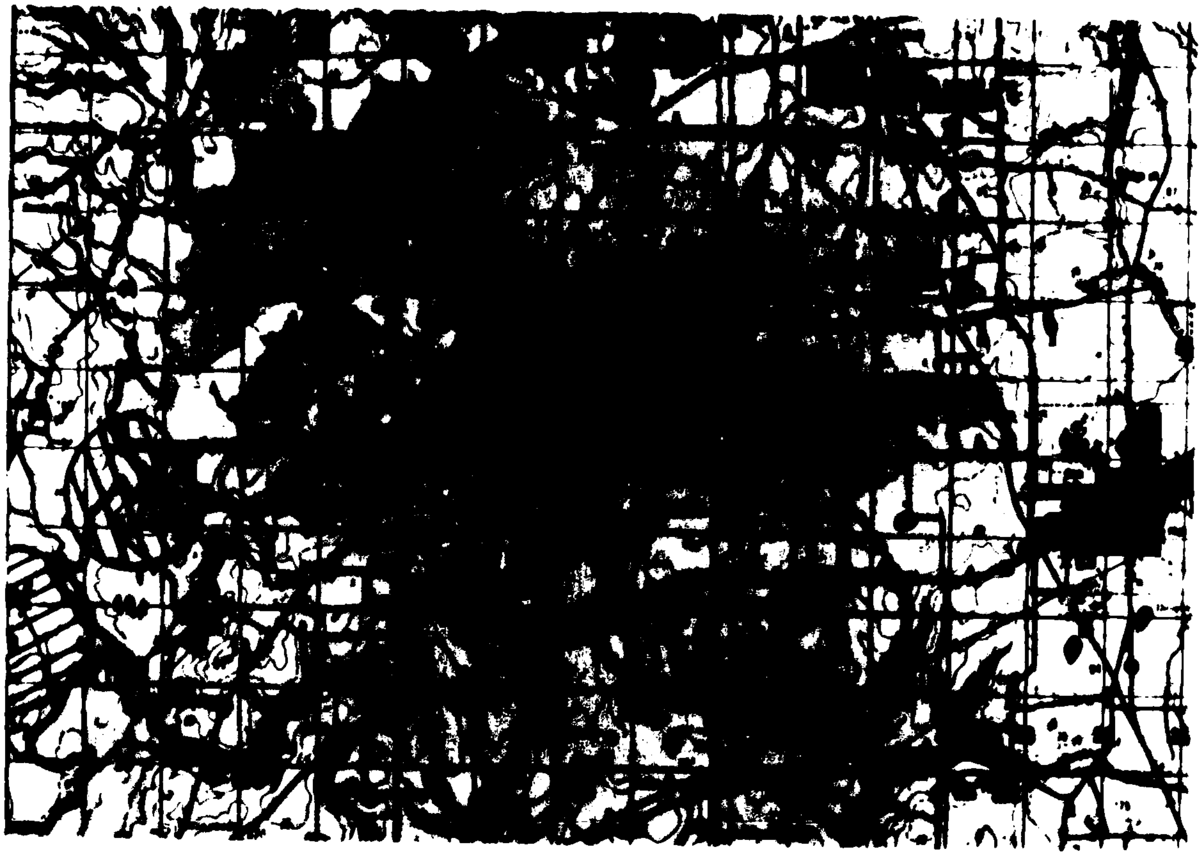

FIGURE B-3. Nap-of-the-earth navigation course no. 3.

Appendix C

DERIVATIONS OF REPORTED COMMUNICATION DATA

Investigators use different methods to derive means from communication data. Thus, the derivations of the means and standard deviations reported in Table 4 of this report are presented in this appendix.

Let "a" represent the number of navigation systems used where:

$$i = 1, 2, 3 = a.$$

Let "b" represent the number of navigation courses flown where:

$$j = 1, 2, 3 = b.$$

There were two replications of each possible navigation system (a_i)/course (b_j) combination. The number of replications is represented by n where:

$$k = 1, 2 = n.$$

The experimental design is presented in Table C.1 (Montgomery, D.C. 1976. Design and analysis of experiments. New York: John Wiley & Sons. 418 p.) Notation specific to the communication data is presented in Table C.2.

TABLE C.1

Experimental Design

		NAVIGATION SYSTEM a_1	a_2	a_3	
		y_{111}	y_{121}	y_{131}	
	b_1				$y_{1..}$
		y_{112}	y_{122}	y_{132}	
		y_{211}	y_{221}	y_{231}	
COURSES	b_2				$y_{2..}$
		y_{212}	y_{222}	y_{232}	
		y_{311}	y_{321}	y_{331}	
	b_3				$y_{3..}$
		y_{312}	y_{322}	y_{332}	
		$y_{.1.}$	$y_{.2.}$	$y_{.3.}$	$y_{...}$

TABLE C.2

COMMUNICATION DATA NOTATION

NOTATION	DENOTATION
m_{ijl}	number of navigation messages exchanged between the copilot/navigator (subject) and the pilot while flying with the i th navigation system (i = 1, 2, 3 = a) on the j th course (j = 1, 2, 3 = b) in the k th replicate (k = 1, 2 = n)
$m_{i..}$	total number of navigation messages while flying with the i th navigation system summed over the three courses and both replicates
$m_{.j.}$	total number of navigation messages while flying on the j th course summed over the three navigation systems and both replicates
t_{ijk}	time (duration) of a navigation message with i, j, and k as defined above
T_{ijk}	total time of all navigation messages with i, j, and k as defined above
F_{ijk}	total flight time from the initial point to the release point with i, j, and k as defined above
R_{ijk}	rate of navigation message exchange in navigation messages per minute with i, j, and k as defined above
P_{ijk}	proportion of total flight time (F_{ijk}) spent in navigation communication

The values reported in Table 4 of this report were derived as shown below.

Number of navigation messages

1. The mean number of navigation messages per flight for a navigation system is:

$$\bar{m}_{i..} = \sum_{j=1}^{b} \sum_{k=1}^{n} m_{ijk} \, / \, bn \quad .$$

2. The standard deviation of $m_{i..}$ is:

$$s_{\bar{m}_{i..}} = [\sum_{j=1}^{b} \sum_{k=1}^{n} (m_{ijk} - \sum_{j=1}^{b} \sum_{k=1}^{n} m_{ijk} /bn)^2 \, / \, (bn-1)]^{.5} \quad .$$

3. The mean number of navigation messages per flight for a navigation course is:

$$\bar{m}_{.j.} = \sum_{i=1}^{a} \sum_{k=1}^{n} m_{ijk} /an \quad .$$

4. The standard deviation of $m_{.j.}$ is:

$$s_{\bar{m}_{i..}} = [\sum_{i=1}^{a} \sum_{k=1}^{n} (m_{ijk} - \sum_{i=1}^{a} \sum_{k=1}^{n} m_{ijk} /an)^2 \, / \, (an-1)]^{.5} \quad .$$

Navigation message rate

1. The mean number of navigation messages exchanged per minute for a navigation system is:

$$\bar{R}_{i..} = \sum_{j=1}^{b} \sum_{k=1}^{n} (m_{ijk} / f_{ijk})/bn \quad .$$

2. The standard deviation of $R_{i..}$ is:

$$s_{\overline{R}_{i..}} = [\sum_{j=1}^{b} \sum_{k=1}^{n} (m_{ijk}/F_{ijk} - \sum_{j=1}^{b} \sum_{k=1}^{n} (m_{ijk}/F_{ijk})/bn)^2 / (bn-1)]^{.5} .$$

3. The mean number of navigation messages exchanged per minute for a navigation course is:

$$\overline{R}_{.j.} = \sum_{i=1}^{a} \sum_{k=1}^{n} (n_{ijk},F_{ijk}) / an .$$

4. The standard deviation of $\overline{R}_{.j.}$ is:

$$s_{\overline{R}_{.j.}} = [\sum_{i=1}^{a} \sum_{k=1}^{n} (m_{ijk}/F_{ijk} - \sum_{i=1}^{a} \sum_{k=1}^{n} (m_{ikj}/F_{ijk})/an)^2 / (an-1)]^{.5} .$$

<u>Time of a navigation message</u>

1. The mean time of a navigation message on a flight for a navigation system is:

$$\overline{t}_{i..} = \sum_{j=1}^{b} \sum_{k=1}^{n} (t_{ijk}/m_{ijk}) / bn .$$

2. The standard deviation of $t_{i..}$ is:

$$s_{\overline{t}_{i..}} = [\sum_{j=1}^{b} \sum_{k=1}^{n} (t_{ijk}/m_{ijk} - \sum_{j=1}^{b} \sum_{k=1}^{n} (T_{ijk}/m_{ijk})/bn)^2 / (bn-1)^{.5} .$$

3. The mean time of a navigation message on a flight for a navigation course is:

$$\bar{t}_{.j.} = \sum_{j=1}^{a} \sum_{k=1}^{n} (t_{ijk} / m_{ijk}) / an .$$

4. The standard deviation of $\bar{t}_{.j.}$ is:

$$s_{\bar{t}.j.} = [\sum_{i=1}^{a} \sum_{k=1}^{n} (T_{ijk} / m_{ijk} - \sum_{i=1}^{a} \sum_{k=1}^{n} (T_{ijk} / m_{ijk})/an)^{2} / (an-1)]^{.5} .$$

<u>Total time of a navigation message</u>

1. The mean total time of all navigation messages on a flight for a navigation system is:

$$\bar{T}_{i..} = \sum_{j=1}^{b} \sum_{k=1}^{n} T_{ijk} / bn .$$

2. The standard deviation of $\bar{T}_{i..}$ is:

$$s_{\bar{T}_{i..}} = [\sum_{j=1}^{b} \sum_{k=1}^{n} (T_{ijk} - \sum_{j=1}^{b} \sum_{k=1}^{n} T_{ijk} /bn) / (bn-1)] .$$

3. The mean total time of all navigation messages on a flight for a navigation system is:

$$\bar{T}_{.j.} = \sum_{i=1}^{a} \sum_{k=1}^{n} T_{ijk} / an .$$

4. The standard deviation of $\bar{T}_{.j.}$ is:

$$s_{\bar{T}_{.j.}} = \left[\sum_{i=1}^{a} \sum_{k=1}^{n} \left(T_{ijk} - \sum_{i=1}^{a} \sum_{k=1}^{n} T_{ijk} / an\right)^2 / (an-1)\right]^{.5} .$$

Proportion of time in navigation communication

1. The mean proportion of time in navigation communication during a flight for a navigation system is:

$$\bar{P}_{i..} = \sum_{j=1}^{b} \sum_{k=1}^{n} (T_{ijk} / F_{ijk}) .$$

2. The mean proportion of time in navigation communication during a flight for a course is:

$$\bar{P}_{.j.} = \sum_{i=1}^{a} \sum_{k=1}^{n} (T_{ijk} / F_{ijk}) .$$

Appendix D

DERIVATIONS OF REPORTED EYE MOVEMENT DATA

Investigators use different methods to derive means from raw eye movement data. Thus, the derivations of the means and standard deviations reported in Tables 5, 6, 7, and 8 of this report are presented in this appendix.

Let "a" represent the number of navigation systems used where:

$$i = 1, 2, 3 = a.$$

Let "b" represent the number of navigation courses flown where:

$$j = 1, 2, 3 = b.$$

Let "c" represent the number of observation areas into which the copilot/navigator's visual point-of-regard was categorized where:

$$l = 1, 2, 3, \ldots, 7 = c.$$

There were two replications of each possible navigation system (a_i)/course (b_j) combination. The number of replications is represented by n where:

$$k = 1, 2 = n.$$

The experimental design is presented in Table D.1 (Montgomery, D.C. 1976. *Design and analysis of experiments*. New York: John Wiley & Sons. 418 p.) Notation specific to the communication data is presented in Table D.2.

TABLE D.1

Experimental Design

		NAVIGATION SYSTEM			
		a_1	a_2	a_3	
COURSES	b_1	y_{111}	y_{121}	y_{131}	$y_{1..}$
		y_{112}	y_{122}	y_{132}	
	b_2	y_{211}	y_{221}	y_{231}	$y_{2..}$
		y_{212}	y_{222}	y_{232}	
	b_3	y_{311}	y_{321}	y_{331}	$y_{3..}$
		y_{312}	y_{322}	y_{332}	
		$y_{.1.}$	$y_{.2.}$	$y_{.3.}$	$y_{...}$

TABLE D.2

EYE MOVEMENT DATA NOTATION

NOTATION	DENOTATION
v_{ijkl}	number of observations in the l th area (l = 1, 2, 3,..., 7 = c) by the copilot/navigator while flying with the i th navigation system (i = 1, 2, 3 = a) on the j th course (j = 1, 2, 3 = b) in the k th replication (k = 1, 2 = n)
$v_{i..l}$	total number of observations in the l th area while flying with the i th navigation system summed over the three courses and both replicates
$v_{.j.l}$	total number of observations in the l th area while flying on the j th course summed over the three navigation systems and both replicates
t_{ijkl}	time (sec) of an observation in the l th area with i, j, and k as defined above
T_{ijkl}	total time (sec) of all observations in the l th area with i, j, and k as defined above
$T_{i..l}$	total time (sec) of all observations in the l th area while flying with the i th navigation system summed over the three courses and both replicates
$T_{.j.l}$	total time (sec) of all observations in the l th area while flying on the j th course summed over the three navigation systems and both replicates
r_{ijkl}	the observation rate on area l in number of observations per minute with i, j, and k as defined above

TABLE D.2 CONTINUED

$r_{ijk.}$	the overall observation rate on all areas in number of observations per minute with i, j, and k as defined above
PV_{ijkl}	proportion of observations in all areas spent in area l with i, j, and k as defined above
PT_{ijkl}	proportion of time of all observations in all areas spent in area l with i, j, and k as defined above

The values reported in Tables 5, 6, 7, and 8 of this report were derived as shown below.

<u>Time derivations</u>

1. The mean proportion of the total time of all observations in all areas spent in an area for a navigation system is:

$$\overline{PT}_{i..l} = \sum_{j=1}^{b} \sum_{k=1}^{n} (T_{ijkl} / \sum_{l=1}^{c} T_{ijkl}) / bn \quad .$$

2. The standard deviation of $\overline{PT}_{i..l}$ is:

$$s_{\overline{PT}_{i..l}} = [\sum_{j=1}^{b} \sum_{k=1}^{n} (T_{ijkl} / \sum_{l=1}^{c} T_{ijkl} - \sum_{j=1}^{b} \sum_{k=1}^{n} (T_{ijkl} / \sum_{l=1}^{c} T_{ijkl})/bn)^2 / (bn-1)]^{.5} \quad .$$

3. The mean proportion of the total time of all observations in all areas spent in an area for a navigation course is:

$$\overline{PT}_{.j.l} = \sum_{i=1}^{a} \sum_{k=1}^{n} (T_{ijkl} / \sum_{l=1}^{c} T_{ijkl}) / an \quad .$$

4. The standard deviation of $\overline{PT}_{.j.l}$ is:

$$s_{\overline{PT}_{.j.l}} = [\sum_{i=1}^{a} \sum_{k=1}^{n} (T_{ijkl} / \sum_{l=1}^{c} T_{ijkl} - \sum_{i=1}^{a} \sum_{k=1}^{n} (T_{ijkl} / \sum_{l=1}^{c} T_{ijkl})/an)^2 / (an-1)]^{.5} \quad .$$

Frequency derivations

1. The mean proportion of the total number of all observations in all areas spent in an area for a navigation system is:

$$\overline{PV}_{i..l} = \sum_{j=1}^{b} \sum_{k=1}^{n} (v_{ijkl} / \sum_{l=1}^{c} v_{ijkl}) / bn \quad .$$

2. The standard deviation of $\overline{PV}_{i..l}$ is:

$$s_{\overline{PV}_{i..l}} = [\sum_{j=1}^{b} \sum_{k=1}^{n} (v_{ijkl} / \sum_{l=1}^{c} v_{ijkl} - \sum_{j=1}^{b} \sum_{k=1}^{n} (v_{ijkl} / \sum_{l=1}^{n} v_{ijkl})/bn)^{2} / (bn-1)]^{.5} \quad .$$

3. The mean proportion of the total number of all observations in all areas spent in an area for a navigation course is:

$$\overline{PV}_{.j.l} = \sum_{i=1}^{a} \sum_{k=1}^{n} (v_{ijkl} / \sum_{l=1}^{c} v_{ijkl}) / an \quad .$$

4. The standard deviation of $\overline{PV}_{.j.l}$ is:

$$s_{\overline{PV}_{.j.l}} = [\sum_{i=1}^{a} \sum_{k=1}^{n} (v_{ijkl} / \sum_{l=1}^{c} v_{ijkl} - \sum_{i=1}^{a} \sum_{k=1}^{n} (v_{ijkl} / \sum_{l=1}^{n} v_{ijkl})/an)^{2} / (an-1)]^{.5} \quad .$$

Frequency / time derivations

1. The mean duration (sec) of an observation in an area for a navigation system is:

$$\bar{t}_{i..l} = \sum_{j=1}^{b} \sum_{k=1}^{n} (T_{ijkl} / v_{ijkl}) / bn \quad .$$

2. The standard deviation of $\bar{t}_{i..l}$ is:

$$s_{\bar{t}_{i..l}} = \left[\sum_{j=1}^{b} \sum_{k=1}^{n} \left(T_{ijkl} / v_{ijkl} - \sum_{j=1}^{b} \sum_{k=1}^{n} (T_{ijkl} / v_{ijkl})/bn\right)^{2} / (bn-1) \right]^{.5} \quad .$$

3. The mean duration (sec) of an observation in an area for a navigation course is:

$$\bar{t}_{.j.l} = \sum_{i=1}^{a} \sum_{k=1}^{n} (T_{ijkl} / v_{ijkl})/an \quad .$$

4. The standard deviation of $\bar{t}_{.j.l}$ is:

$$s_{\bar{t}_{.j.l}} = \left[\sum_{i=1}^{a} \sum_{k=1}^{n} \left(T_{ijkl} / v_{ijkl} - \sum_{j=1}^{a} \sum_{k=1}^{n} (T_{ijkl} / v_{ijkl})/an\right)^{2} / (an-1) \right]^{.5} \quad .$$

5. The overall mean observation rate on all areas in number of observations per minute for a navigation system is:

$$\bar{r}_{i...} = \sum_{j=1}^{b} \sum_{k=1}^{n} \left(\left(60 \sum_{l=1}^{c} v_{ijkl}\right) / \sum_{l=1}^{c} T_{ijkl} \right) / bn \quad .$$

6. The standard deviation of $\bar{r}_{i...}$ is:

$$s_{\bar{r}_{i...}} = [\sum_{j=1}^{b}\sum_{k=1}^{n}(60\sum_{l=1}^{c}v_{ijkl} / \sum_{l=1}^{c}T_{ijkl} -$$

$$\sum_{j=1}^{b}\sum_{k=1}^{n}((60\sum_{l=1}^{c}v_{ijkl})/\sum_{l=1}^{c}T_{ijkl})/bn)^{2} / (bn-1)]^{.5} .$$

7. The overall mean observation rate on all areas in terms of the number of observations per minute for a navigation course is:

$$\bar{r}_{.j..} = \sum_{i=1}^{a}\sum_{k=1}^{n}((60\sum_{l=1}^{c}v_{ijkl})/\sum_{l=1}^{c}T_{ijkl}) / an .$$

8. The standard deviation of $\bar{r}_{.j..}$ is:

$$s_{\bar{r}_{.j..}} = [\sum_{i=1}^{a}\sum_{k=1}^{n}(60\sum_{l=1}^{c}v_{ijkl} / \sum_{l=1}^{c}T_{ijkl} -$$

$$\sum_{i=1}^{a}\sum_{k=1}^{n}((60\sum_{l=1}^{c}v_{ijkl})/\sum_{l=1}^{c}T_{ijkl})/an)^{2} / (an-1)]^{.5} .$$

9. The mean observation rate on an area in number of observations per minute for a navigation system is:

$$\bar{r}_{i..l} = \sum_{j=1}^{b}\sum_{k=1}^{n}(60v_{ijkl} / T_{ijkl}) / bn .$$

10. The standard deviation of $\bar{r}_{i..l}$ is:

$$s_{\bar{r}_{i..l}} = \left[\sum_{j=1}^{b} \sum_{k=1}^{n} (60v_{ijkl}/T_{ijkl} - \sum_{j=1}^{b} \sum_{k=1}^{n} (60v_{ijkl}/T_{ijkl})/bn)^2 / (bn-1) \right]^{.5} .$$

11. The mean observation rate on an area in number of observations per minute for a navigation course is:

$$\bar{r}_{.j.l} = \sum_{i=1}^{a} \sum_{k=1}^{n} (60v_{ijkl}/T_{ijkl}) /an .$$

12. The standard deviation of $\bar{r}_{.j.l}$ is:

$$s_{\bar{r}_{.j.l}} = \left[\sum_{i=1}^{a} \sum_{k=1}^{n} (60v_{ijkl}/T_{ijkl} - \sum_{i=1}^{a} \sum_{k=1}^{n} (60v_{ijkl}/T_{ijkl})/an)^2 / (an-1) \right]^{.5} .$$

Appendix E

NAVIGATION PERFORMANCE DATA

TABLE E.1

FREQUENCY AND MAGNITUDE OF NAVIGATION DELAYS
BY THE HAND-HELD MAP GROUP

Delay	Course 1		Course 2		Course 3	
Subject S_{ijk} +	S_{111}	S_{112}	S_{211}	S_{212}	S_{311}	S_{312}
Stop		1				1
Stop & pop-up						2
Stop & 360° turn	2					
Retrack (180° turn)		1				1
Deviation						
magnitude *						
False ID	3			2		1
magnitude * (s)	340 1230 1190			910 1940		780

* Vector error (in meters) from intended track

\+ i = course where: 1 = course 1
2 = course 2
3 = course 3

j = navigation system where: 1 = Hand-Held Map
2 = Doppler Navigation System
3 = Projected Map System

k = replications where: [illegible] = first replication
[illegible] = second replication

TABLE E.2

FREQUENCY AND MAGNITUDE OF NAVIGATION DELAYS
BY THE DOPPLER NAVIGATION SYSTEM GROUP

Delay	Course					
	1		2		3	
Stop		1		1		
Stop & pop-up						
Stop & 360° turn	1					
Retrack (180° turn)						
Deviation		1		1	2	1
magnitude (s)*		320		530	830 560	560
False ID		1				
magnitude*		940				
Subject+	S_{111}	S_{112}	S_{211}	S_{212}	S_{311}	S_{312}

* Vector error (in meters) from intended track

\+ i = course where: 1 = course 1
2 = course 2
3 = course 3

j = navigation system where: 1 = Hand-Held Map
2 = Doppler Navigation System
3 = Projected Map System

k = replications where: 1 = first replication
2 = second replication

TABLE E.3

FREQUENCY AND MAGNITUDE OF NAVIGATION DELAYS
BY THE PROJECTED MAP SYSTEM GROUP

Delay	Course					
	1		2		3	
Stop						
Stop & pop-up						
Stop & 360° turn						
Retrack (180° turn)						
Deviation		1				1
magnitude*		900				200
False ID		3				
magnitude*		1480 970 1310				
Subject+ S_{ijk}	S_{111}	S_{112}	S_{211}	S_{212}	S_{311}	S_{312}

* Vector error (in meters) from intended track

+ i = course where: 1 = course 1
2 = course 2
3 = course 3

j = navigation system where: 1 = Hand-Held Map
2 = Doppler Navigation System
3 = Projected Map System

k = replications where: 1 = first replication
2 = second replication

Appendix F

NAVIGATION PERFORMANCE ANALYSES

TABLE F.1

AIRSPEED ANOVA SUMMARY TABLE

SOURCE	df	MS	F	P
NAVIGATION SYSTEM (NS)	2	108.56	8.05	0.010
COURSE (C)	2	44.13	3.27	0.085
NS x C	4	9.15	0.68	0.623
ERROR	9	13.47		
TOTAL	17	175.31		

TABLE F.2

AIRSPEED ANOVA SUMMARY TABLE (POOLED ERROR)

SOURCE	df	MS	F	P
NAVIGATION SYSTEM (NS)	2	108.56	8.94	0.004
COURSE (C)	2	44.13	3.63	0.056
ERROR	13	12.15		
TOTAL	17	164.84		

TABLE F.3

FLIGHT TIME ANOVA SUMMARY TABLE

SOURCE	df	MS	F	P
NAVIGATION SYSTEM (NS)	2	66.41	1.94	0.199
COURSE (C)	2	81.84	2.39	0.147
NS x C	4	14.70	0.43	0.784
ERROR	9	34.26		
TOTAL	17	197.21		

TABLE F.4

FLIGHT TIME ANOVA SUMMARY TABEL (POOLED ERROR)

SOURCE	df	MS	F	p
NAVIGATION SYSTEM (NS)	2	66.41	2.35	0.134
COURSE (C)	2	81.84	2.90	0.091
POOLED ERROR	13	28.24		
TOTAL	17	176.49		

TABLE F.5

DISTANCE FLOWN ANOVA SUMMARY TABLE

SOURCE	df	MS	F	P
NAVIGATION SYSTEM (NS)	2	20.03	1.21	0.342
COURSE (C)	2	197.55	11.96	0.003
NS x C	4	3.09	0.19	1.000
ERROR	9	16.51		
TOTAL	17	237.18		

TABLE F.6

DISTANCE FLOWN ANOVA SUMMARY TABLE (POOLED ERROR)

SOURCE	df	MS	F	P
NAVIGATION SYSTEM (NS)	2	20.03	1.62	0.236
COURSE (C)	2	197.55	15.96	0.0003
POOLED ERROR	13	12.38		
TOTAL	17	229.96		

Appendix G

COMMUNICATION WORKLOAD DATA

TABLE G.1

COMMUNICATION WORKLOAD DATA

SUBJECT ijk *	NUMBER OF MESSAGES	TIME (min) IN NAVIGATION COMMUNICATION	FLIGHT TIME (min)
S 111	129	8.57	29.17
S 112	161	9.12	39.28
S 211	125	6.72	31.77
S 212	93	4.69	28.72
S 311	85	6.82	25.17
S 312	133	13.50	43.18
S 121	106	5.76	30.06
S 122	117	7.62	37.73
S 221	57	2.04	20.15
S 222	100	6.80	25.97
S 321	97	7.79	27.50
S 322	67	5.03	24.25
S 131	91	7.69	36.00
S 132	146	8.32	27.20
S 231	113	5.18	25.38
S 232	85	7.35	25.22
S 331	90	6.12	23.38
S 3 2	74	7.85	23.20

* i = courses where: 1 = course 1
2 = course 2
3 = course 3

j = navigation system where: 1 = hand-held map
2 = Doppler navigation system
3 = projected map system

k = replications where: 1 = first replication
2 = second replication

Appendix H

COMMUNICATION WORKLOAD ANALYSES

TABLE H.1

MESSAGES/FLIGHT ANOVA SUMMARY TABLE

SOURCE	df	MS	F	p
NAVIGATION SYSTEM (NS)	2	1452.17	2.32	0.154
COURSE (C)	2	2046.50	3.26	0.086
NS x C	4	70.92	0.11	1.000
ERROR	9	627.06		
TOTAL	17	4196.65		

TABLE H.2

MESSAGES/FLIGHT ANOVA SUMMARY TABLE (POOLED ERROR)

SOURCE	df	MS	F	p
NAVIGATION SYSTEM (NS)	2	1452.17	3.19	0.075
COURSE (C)	2	2046.50	4.49	
POOLED ERROR	13	455.94		
TOTAL	17	3954.61		

TABLE H.3

MESSAGES/MIN ANOVA SUMMARY TABLE

SOURCE	df	MS	F	p
NAVIGATION SYSTEM (NS)	2	0.58	0.82	0.472
COURSE (C)	2	0.54	0.77	0.493
NS x C	4	0.10	0.14	1.000
ERROR	9	0.71		
TOTAL	17	1.93		

TABLE H.4

MESSAGES/MIN ANOVA SUMMARY TABLE (POOLED ERROR)

SOURCE	df	MS	F	p
NAVIGATION SYSTEM (NS)	2	0.58	1.11	0.359
COURSE (C)	2	0.54	1.04	0.380
POOLED ERROR	13	0.52		
TOTAL	17	1.64		

TABLE H.5

MEAN TIME/MESSAGE ANOVA SUMMARY TABLE

SOURCE	df	MS	F	p
NAVIGATION SYSTEM (NS)	2	0.72	0.64	0.548
COURSE (C)	2	4.71	[illegible]	0.051
NS x C	4	0.17	0.15	1.000
ERROR	9	1.12		
TOTAL	17	6.72		

TABLE H.6

MEAN TIME/MESSAGE ANOVA SUMMARY TABLE (POOLED ERROR)

SOURCE	df	MS	F	p
NAVIGATION SYSTEM (NS)	2	0.72	0.87	[illegible]
COURSE (C)	2	4.71	[illegible]	[illegible]
POOLED ERROR	13	[illegible]		
TOTAL	17	[illegible]		

TABLE H.7

TIME/FLIGHT IN NAVIGATION COMMUNICATION ANOVA SUMMARY TABLE

SOURCE	df	MS	F	p
NAVIGATION SYSTEM (NS)	2	8.62	1.71	0.235
COURSE (C)	2	11.38	2.25	0.160
NS x C	4	1.84	0.37	0.828
ERROR	9	5.05		
TOTAL	17	26.88		

TABLE H.8

TIME/FLIGHT IN NAVIGATION COMMUNICATION
ANOVA SUMMARY TABLE (POOLED ERROR)

SOURCE	df	MS	F	p
NAVIGATION SYSTEM (NS)	2	8.62	2.12	0.159
COURSE (C)	2	11.38	2.80	0.097
POOLED ERROR	13	4.06		
TOTAL	17	24.06		

TABLE H.9

PROPORTION OF FLIGHT TIME IN NAVIGATION COMMUNICATION
ANOVA SUMMARY TABLE

SOURCE	df	MS	F	p
NAVIGATION SYSTEM (NS)	2	0.01	1.67	0.242
COURSE (C)	2	0.01	2.42	0.144
NS x C	4	0.01	0.19	1.000
ERROR	9	0.01		
TOTAL	17	0.04		

TABLE H.10

PROPORTION OF FLIGHT TIME IN NAVIGATION COMMUNICATION
ANOVA SUMMARY TABLE (POOLED ERROR)

SOURCE	df	MS	F	p
NAVIGATION SYSTEM (NS)	2	0.01	2.22	0.148
COURSE (C)	2	0.01	3.22	0.073
POOLED ERROR	13	0.01		
TOTAL	17	0.03		

Appendix I

VISUAL WORKLOAD ANALYSES

TABLE I.1

OBSERVATIONS/MIN OVERALL ANOVA SUMMARY TABLE

SOURCE	df	MS	F	p
NAVIGATION SYSTEM (NS)	2	166.74	7.03	0.015
COURSE (C)	2	16.60	0.70	0.522
NS x C	4	25.89	1.09	0.415
ERROR	9	23.73		
TOTAL	17	232.96		

TABLE I.2

OBSERVATIONS/MIN OVERALL ANOVA SUMMARY TABLE (POOLED ERROR)

SOURCE	df	MS	F	p
NAVIGATION SYSTEM (NS)	2	166.74	6.83	0.009
COURSE (C)	2	16.60	0.68	0.524
POOLED ERROR	13	24.42		
TOTAL	17	207.76		

TABLE I.3

OBSERVATIONS/MIN OUTSIDE ANOVA SUMMARY TABLE

SOURCE	df	MS	F	p
NAVIGATION SYSTEM (NS)	2	47.31	13.09	0.002
COURSE (C)	2	0.77	0.21	0.813
NS x C	4	3.84	1.06	0.428
ERROR	9	3.61		
TOTAL	17	55.53		

TABLE I.4

OBSERVATIONS/MIN OUTSIDE ANOVA SUMMARY TABLE (POOLED ERROR)

SOURCE	df	MS	F	p
NAVIGATION SYSTEM (NS)	2	47.31	12.84	0.001
COURSE (C)	2	0.77	0.21	0.815
POOLED ERROR	13	3.68		
TOTAL	17	51.76		

TABLE I.5

OBSERVATIONS/MIN ON NAVIGATION SYSTEM ANOVA SUMMARY TABLE

SOURCE	df	MS	F	p
NAVIGATION SYSTEM (NS)	2	7.94	1.21	0.341
COURSE (C)	2	1.88	0.29	0.757
NS x C	4	3.71	0.57	0.693
ERROR	9	6.54		
TOTAL	17	20.07		

TABLE I.6

OBSERVATIONS/MIN ON NAVIGATION SYSTEM
ANOVA SUMMARY TABLE (POOLED ERROR)

SOURCE	df	MS	F	p
NAVIGATION SYSTEM (NS)	2	7.94	1.41	0.281
COURSE (C)	2	1.88	0.33	0.723
POOLED ERROR	13	5.67		
TOTAL	17	15.45		

TABLE I.7

PROPORTION OF OBSERVATIONS OUTSIDE ANOVA SUMMARY TABLE

SOURCE	df	MS	F	p
NAVIGATION SYSTEM (NS)	2	84.61	34.93	0.0001
COURSE (C)	2	14.42	5.95	0.023
NS x C	4	8.21	3.39	0.059
ERROR	9	2.24		
TOTAL	17	109.48		

TABLE I.8

PROPORTION OF OBSERVATIONS OUTSIDE
ANOVA SUMMARY TABLE (POOLED ERROR)

SOURCE	df	MS	F	p
NAVIGATION SYSTEM (NS)	2	84.61	20.14	0.0001
COURSE (C)	2	14.42	3.43	0.064
POOLED ERROR	13	4.20		
TOTAL	17	103.23		

TABLE I.9

PROPORTION OF TIME ON NAVIGATION SYSTEM ANOVA SUMMARY TABLE

SOURCE	df	MS	F	p
NAVIGATION SYSTEM (NS)	2	138.76	2.34	0.152
COURSE (C)	2	124.77	2.10	0.178
NS x C	4	78.33	1.32	0.334
ERROR	9	59.32		
TOTAL	17	401.18		

TABLE I.10

PROPORTION OF TIME ON NAVIGATION SYSTEM
ANOVA SUMMARY TABLE (POOLED ERROR)

SOURCE	df	MS	F	p
NAVIGATION SYSTEM (NS)	2	138.76	2.13	0.159
COURSE (C)	2	124.77	1.91	0.187
POOLED ERROR	13	65.17		
TOTAL	17	328.70		

TABLE I.11

PROPORTION OF TIME OUTSIDE ANOVA SUMMARY TABLE

SOURCE	df	MS	F	p
NAVIGATION SYSTEM (NS)	2	214.70	4.43	0.046
COURSE (C)	2	110.85	2.29	0.157
NS x C	4	37.58	0.78	0.568
ERROR	9	48.43		
TOTAL	17	411.56		

TABLE I.12

PROPORTION OF TIME OUTSIDE ANOVA SUMMARY TABLE (POOLED ERROR)

SOURCE	df	MS	F	p
NAVIGATION SYSTEM (NS)	2	214.70	4.76	0.028
COURSE (C)	2	110.85	2.46	0.124
POOLED ERROR	13	45.09		
TOTAL	17	370.64		

TABLE I.13

PROPORTION OF TIME NAVIGATING ANOVA SUMMARY TABLE

SOURCE	df	MS	F	p
NAVIGATION SYSTEM (NS)	2	119.62	4.69	0.040
COURSE (C)	2	6.62	0.26	0.777
NS x C	4	10.08	0.40	0.807
ERROR	9	25.50		
TOTAL	17	161.82		

TABLE I.14

PROPORTION OF TIME NAVIGATING ANOVA SUMMARY TABLE (POOLED ERROR)

SOURCE	df	MS	F	p
NAVIGATION SYSTEM (NS)	2	119.62	5.76	0.016
COURSE (C)	2	6.62	0.32	0.732
POOLED ERROR	13	20.75		
TOTAL	17	146.99		

TABLE I.15

MEAN TIME/OBSERVATION OUTSIDE ANOVA SUMMARY TABLE

SOURCE	df	MS	F	p
NAVIGATION SYSTEM (NS)	2	16.09	14.40	0.002
COURSE (C)	2	0.75	0.67	0.534
NS x C	4	0.65	0.58	0.682
ERROR	9	1.12		
TOTAL	17	18.61		

TABLE I.16

MEAN TIME/OBSERVATION OUTSIDE ANOVA SUMMARY TABLE (POOLED ERROR)

SOURCE	df	MS	F	p
NAVIGATION SYSTEM (NS)	2	16.09	16.51	0.0003
COURSE (C)	2	0.75	0.77	0.482
POOLED ERROR	13	0.97		
TOTAL	17	17.81		

Appendix J

VISUAL WORKLOAD DATA

TABLE J.1
VISUAL WORKLOAD DATA

SUBJECT ijk*	TIME (sec) IN AREA / OBSERVATIONS IN AREA+ 1	2	3	4	5	6	7
S 111	551/214	429/206	25/23	93/8			
S 112	850/286	491/286	112/60	127/11			
S 211	534/132	342/121	52/30	129/7			
S 212	260/108	325/114	15/15	28/3			
S 311	373/101	227/97	38/20	78/9			
S 312	511/226	509/230	39/28	13/3			
S 121	366/196	254/175	77/67	157/26	16/11		
S 122	824/204	248/131	109/88	97/9	35/17		
S 221	337/151	142/104	92/82	33/12	7/8		
S 222	301/157	253/139	67/57	82/12	9/7		
S 321	301/118	226/89	35/29	77/12	10/8		
S 322	303/129	282/104	28/26	36/5	23/9		
S 131	1022/166	256/148	47/35	64/6		45/22	0.4/1
S 132	575/95	208/88	30/18	70/6		52/30	0.7/1
S 231	270/88	150/89	35/27	38/7		71/36	0.8/1
S 232	341/57	194/58	31/13	28/4		56/22	8.1/3
S 331	384/72	117.64	36/26	67/6		48/24	1.7/1
S 332	420/63	114/59	22/14	34/5		33/18	4.9/2

* i = courses where: 1 = course 1
2 = course 2
3 = course 3

j = navigation system where: 1 = hand-held map
2 = Doppler navigation system
3 = projected map system

k = replications where: 1 = first replication
2 = second replication

+ Areas where :

1 = outside 3 = instrument panel 5 = Doppler
2 = hand-held map 4 = free time task 6 = map display
7 = projected map system navigation control unit

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