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HELICOPTER COPILOT WORKLOAD DURING NAP-OF-THE-EARTH FLIGHT
(Reprint)

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Two automatic navigation systems, a Doppler radar system and a projected map system, and a hand-held map were examined for their effects on copilot/navigator workload and performance. The automatic navigation systems reduced the number of navigation errors and the size of deviations from intended track. The Doppler system reduced the time devoted to navigating and the number of verbal navigation messages exchanged between the pilot and copilot. The projected map system reduced visual workload. However, with all three navigation systems, more than 80% of the copilots' time was spent on navigation tasks, less than 10% of their time was visual "free time" that could be used for other tasks, and greater than 20% of the aircrew's time was occupied with navigation communications.

Helicopter Copilot Workload During Nap-of-the-Earth Flight

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THE U.S. ARMY has considered installing automatic navigation equipment in some of its helicopters to help alleviate the disorientation and high workload problems associated with nap-of-the-earth (NOE) flight (flight as close to the surface of the earth as obstacles and vegetation permit). Two of the many self-contained navigation devices that have been suggested for Army use are Doppler radar navigation systems and pictorial navigation displays. These devices are representative of the various automated components that have been available for several years.

Most of the navigation devices available have been tested for accuracy, aircraft compatibility and useability (3,6). However, none of the tests have objectively determined that these systems reduce the high workload imposed during NOE navigation while at the same time improving navigation performance.

The objectives of the research reported here were to compare the copilot/navigator workload and performance effects of using an automated navigation system (Doppler) and a projected map system to those of using the standard hand-held map system. Two hypotheses formulated were that helicopter copilot navigation *workload* and *performance* at NOE flight levels do not change as a function of navigation system.

MATERIALS AND METHODS

Equipment

Aircraft, navigation systems and visual free-time equipment. Three navigation systems were used. Two automatic dead reckoning systems (a Doppler radar and a projected map system) were installed in an Army JUH-1H utility helicopter specially instrumented for data collection. The third, a baseline navigation system, was the standard 1:50,000 scale topographic hand-held map (HHM).

The Doppler radar, a Singer-Kearfott Co. Lightweight Doppler Navigation System (LDNS AN/ASN–128–XE–2), was a completely self-contained navigation system that did not require any ground-based aids and was capable of providing position information

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from a known starting point. The other automatic navigation system was a Projected Map System (PMS) manufactured by Computing Devices Co. The PMS was not a complete automatic navigation system. It required inputs of groundspeed and drift angle from the Doppler.

An inactive frequency modulation (FM) radio control head was placed in the center pedestal console with the other radios between the two pilots for use in a visual free-time/secondary task.

Data collection equipment. A Helicopter In-Flight Monitoring System (HIMS), fabricated in-house (4) was used to record the heading, airspeed, and flight path of the helicopter.

A National Aeromedical Corps (NAC) Eye Mark Recorder (Fig. 1) and a Photo-Sonic high speed motion picture camera were used to record the copilot/navigator's eye movements on high speed film. This system uses the corneal reflection technique to record the subject's point-of-regard. Simmons (9) provides a description of the eye movement tracking and recording and data reduction equipment.

Communications between the pilot and the copilot were recorded using a Bell and Howell 3181A audio tape recorder connected in parallel with the aircraft intercommunication system.

Fig. 1. Copilot/navigator wearing eye movement camera.

Subjects

Participating in the study were 18 male volunteers (median age = 25 years), all recent Army rotary wing aviator graduates. Each had 175 training flight hours, of which 30 h involved terrain flight navigation.

Experimental Design

A randomized block design with replication was used (2). 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 conjunction with the hand-held map, or the PMS with the hand-held map) on one of 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 (HHM), two with the LDNS, and two with the PMS.

Procedure

Training. All subjects received 2 h of classroom training on the Doppler and projected map systems. Subjects were then assigned to one of the three navigation system conditions: HHM, LDNS, or PMS. Subjects were shown how to operate the systems with the helicopter on the ground and were given in-flight training with the navigation system they would use.

Conduct of test flights. The day of their test flight, subjects were given a 1:50,000 scale topographic map of the area in which they were to navigate. The map contained a distinctively marked start point, a finish point and eight labeled checkpoints. Subjects planned a tactical NOE course that would bring them from the start point to each of the checkpoints in sequence and finally to the finish point.

The pilot flew the helicopter to the start point on the NOE course given to the subject. The subject then assumed all the duties and responsibilities of the copilot to include: the primary duty of navigation, assisting the pilot in hazard and obstacle avoidance and monitoring the instrument panel. The copilot/subjects were instructed to direct the pilot at appropriate airspeeds to each of the eight checkpoints and the finish point while maintaining an NOE profile. The research pilot played a minimal role in navigating the course.

Once on each flight an attempt was made to disorient the copilot. This was done to determine how well the subjects could navigate from unknown locations with their respective navigation systems. While the copilot worked on an imposed set of arithmetic tasks, the pilot intentionally flew the helicopter off course. Then the copilot was required to direct the pilot back to the correct course. This attempt to disorient the copilot occurred 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 included mean airspeed, time to complete the course, distance flown, and the number of navigation delays or errors. Navigation errors or delays were classified in four categories: 1) stops—stopping the helicopter to regain orientation; 2) retracks—returning to the last known location to reorient; 3) deviations—straying from intended flight path, recognizing the deviation and then re-directing the pilot back to the intended course; and 4) false identifications—incorrect identification of a checkpoint or the finish point.

Verbal communication measures included the number of messages spoken by the copilot and pilot, the average length of time spent communicating a message, the mean number of messages exchanged per min and the total time spent communicating during each flight. A message began when either the pilot or copilot began to speak and ended when the speaker stopped talking.

Eye movement data were film recorded for each subject between five pairs of checkpoints. Subjects were credited with a visual "observation" each time they directed their 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. Data were reduced to frequency counts and durations of observations to each of the seven viewing areas.

An "observation" was any directing of the eyes to a particular location for a scoreable duration of time (roughly 100 ms or longer) and lasted until 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.

RESULTS

Navigation Performance

Of the three measures of navigation performance (mean airspeed, mean flight time, and mean distance flown) examined with analyses of variance, the only significant main effect was that of airspeed ($p < 0.05$). A Duncan's multiple range test revealed that the mean airspeed of the HHM group (26 kn) was significantly slower ($p < 0.05$) than that of the LDNS group (34 kn) and the PMS group (33 kn).

The frequency and magnitude of navigation errors were also examined but not subjected to statistical analyses. The HHM group committed 14 delays, while the LDNS and PMS groups generated 9 and 5 delays, respectively. Disorientations, defined as a retrack or false identification, occurred on four of the six HHM flights while only one disorientation occurred with each of the automatic navigation systems. Median vector error for deviations from intended course was smallest for the LDNS group (560 m, range = 320 to 940 m) and the greatest for the HHM group (1050 m, range = 340 to 1,940 m). The PMS group had a median vector error of 970 m (range = 200 to 1,480 m). These values do not include the attempted intentional disorientation. All subjects realized they had been taken off course and readily directed the pilot back to their desired flight path.

Communication Workload

The HHM, LDNS, and PMS group respectively spent 24%, 21%, and 27% of their flight time in navigation communication. The HHM and PMS groups spoke a navigation message, on the average, every 16 s while the LDNS group communicated a navigation message every 19 s. No significant main effects due to navigation systems were found in the analyses of messages per flight, messages per minute, time per message, or proportion of flight time in navigation communication.

A post hoc Duncan's test on the mean number of messages per flight by each of the groups showed that the HHM group spoke a significantly greater ($p < 0.05$) number of messages (121) than the LDNS group (91).

Visual Workload

The results of the visual workload analyses are presented in Table I.

Observations Outside the Cockpit. Subjects who used the PMS devoted a significantly smaller ($p < 0.05$) proportion (0.39) of their observations outside the cockpit than either of the other two groups (variable 4, Table I). The PMS group also devoted a significantly greater ($p < 0.05$) proportion of their viewing time outside (variable 6, Table I) and made significantly fewer ($p<0.05$) observations per minute outside the helicopter than the LDNS and the HHM groups (variable 2, Table I). 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 I).

Observations toward navigation systems. Summing the eye movement "observation" data toward the three components comprising the PMS navigation system (HHM, PMD, and NCU) yields a measure of the total time the PMS subjects spent viewing their navigation system. Likewise, combining the LDNS subjects' proportion of time devoted to looking at the HHM and the LDNS yields the cumulative proportion of time spent viewing their navigation system. The HHM subjects' navigation system consisted only of the HHM. These combined values are presented as mean proportions in variable 5, Table I.

Navigation task visual workload. The total visual time a subject devoted to the task of navigation can be inferred by adding the proportions of time spent looking at the respective navigation components (variable 5, Table I) and the time spent looking outside the cockpit (variable 6, Table I). The resultant proportion of time spent navigating is variable 7 in Table I. The LDNS group spent a significantly smaller ($p <0.05$) proportion of their time navigating (.81) than either the HHM group (.88) or the PMS group (.89).

Visual free time. Because of the low frequency of observations (less than one per minute) to the free-time task (variable 9, Table I) and possible confounding effects due to the location of the free-time task radio control head close to the LDNS, these data were not statistically tested.

DISCUSSION

Navigation Performance

The navigation performance data are compatible with those collected in several other studies (1,5,7,10). Four of the six HHM subjects became disoriented while using a hand-held map and these subjects had the largest mean vector error for course deviations.

The significant difference ($p < 0.05$) between the HHM group's mean airspeed (26 kn) and the airspeed of the LDNS and PMS groups (34 and 33 kn, respectively) is difficult to interpret. The slower airspeed of an aircrew using a HHM may simply reflect their

TABLE I. VISUAL WORKLOAD MEASURES.

	VISUAL WORKLOAD VARIABLES	MEAN (n = 6)			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 to the 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	0.46[a]	0.44[a]	0.39[b]	34.93	<0.001
5.	Proportion of time on navigation system	0.38[a]	0.31[a]	0.28[a]	2.13	0.159
6.	Proportion of time looking outside	0.49[a]	0.49[a]	0.59[b]	4.76	0.028
7.	Proportion of time navigating	0.88[a]	0.81[b]	0.89[a]	5.76	0.016
8.	Mean time/observation outside	3.0[a]	2.5[a]	5.5[b]	16.51	<0.001
9.	Observation/min on ** free–time task	0.4	0.9	0.5	–	–
10.	Proportion of time ** on free–time task	0.08	0.10	0.06	–	–

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

** Not statistically analyzed

greater number of delays such as stops, disorientations, and incorrect checkpoint identifications, or it may be partially attributable to an overall general tendency to travel slower when using the HHM for navigation. The data here do not permit a definitive answer to that question; but they do point out that helicopter NOE flight in unfamiliar, mixed terrain is conducted at rather slow airspeeds.

An apparent advantage to having an automatic navigation system is the aid it provides to the aircrew in the confirmation of their own belief that they are off course and consequently aiding them in not straying further from their intended track. The automatic navigation system can provide them with their exact location and they can then choose the best route to their destination from their off-course location.

Communication Workload

The only significant effect found in the analyses of the communication data was a simple effect of messages. Fewer navigation messages ($p < 0.05$) were spoken per flight by the LDNS pilot/copilot teams than by the HHM teams, 91 vs. 121, respectively. Although no significant navigation system main effects were obtained between groups, the data do provide some interesting information concerning navigation communication. The members of pilot/copilot teams communicated a navigation message to one another every 20 s and they spent from 21 to 27% of their flight time in navigation communication. These results apply to all navigation systems examined.

In addition to the communications related to navigation, the aircrew has many other tasks that require inter-crew communication and also must communicate with other aircrews and ground personnel. These other tasks also impose a substantial communication workload on the crew. Improvements in communication procedures and terminology for navigation and non-navigation communication tasks may reduce workload and improve aircrew performance.

Visual Workload

Observations outside cockpit. The percentage of visual time the HHM group spent looking outside the cockpit (49%) is similar to that found by Sanders, Simmons and Hofmann (8) and Barnard *et al.* (1), 57% and 50%, respectively. Of the three subject groups in this study, the PMS group spent the greatest percentage of visual time looking outside (59%) and devoted the smallest percentage of observations outside (39%). They also had the smallest observation rate outside (6.7 observations per min) and spent more time outside per observation (5.5 s) than either of the other two groups.

Since the PMS group spent nearly twice as much time per observation outside as the other two groups, one might speculate that larger areas were observed for longer times with each outside observation. The viewing of larger areas could enable the copilot to acquire more terrain information for navigation. Furthermore, the higher proportion of time spent looking outside by the PMS group could aid in the detection of hazards, obstacles, and enemy targets.

Visual workload on navigation task. The time an individual devoted to the navigation task was defined as the sum of: (1) the time spent looking at his navigation equipment, plus (2) the time he spent looking outside. The LDNS subjects spent a smaller proportion of their time navigating than either of the other two groups ($p<0.05$). The results obtained for the HHM group are similar to those obtained by Sanders, Simmons, and Hofmann (8). The HHM group in this study spent 88% of their visual time navigating while Sanders *et al.* 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. That leaves a small proportion of the copilot's time for other duties.

Visual free time. On the average, HHM and PMS subjects looked at the free-time task about once every 2 min (Table I). The rate of observations per min on the free-time task for the HHM group (0.4) is the same as that reported by Sanders *et al.* (8) 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 may be accounted for by the longer time required to perform the free-time task in the present study. The data in Table I indicate that the LDNS group had more visual free time than the other two groups. However, the close proximity of the LDNS computer-display unit to the free-time task radio control head may have influenced subjects to glance at the free-time task when they looked at the LDNS. Consequently, the LDNS free-time data may be confounded.

The PMS may also have provided the copilots with more visual free time since PMS subjects looked to the outside for longer durations than other subjects. If the PMS subjects did have more free time than the other subjects, they apparently used this time to visually search for hazards and obstacles or to confirm their terrain analysis rather than to look at the free-time 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, or reducing workload. 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 alone and still 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.

Although not specifically tested here, perhaps 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 automated systems provide the aircrew with their location and details on how to navigate to a specific point.

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