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Visual Display Delay Effects on Pilot Performance (Reprint)

By

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The Helmet Integrated Display Sight System (HIDSS), originally proposed for the RAH-66 Comanche, displays sensor data from FLIR and image intensifiers, as well as flight instrument and targeting data. All these data will be processed through onboard computers before being displayed on miniature CRT's. In addition to processing delays, delays also are arising from the helmet tracker and from sensor slewing that may increase the total visual display delay to as much as 250 ms. Because display lag is one of the most important limitations affecting the ability of an aviator to use a display, we investigated the effects of 0, 67, 133, 267, 400, and 533 ms visual display delays on the flight performance of 10 volunteer U.S. Army aviators in a full motion flight simulator. There were few performance decrements at 67, 133, or 267 ms delays as compared with the 0 ms delay condition. Significant performance decrements consistently were observed at 400 and 533 ms delays. Given the anticipated visual display delays for the proposed system, flight performance, as measured within the range of flight conditions and profiles examined, should not be affected significantly, although the aviators will experience an increase in workload to compensate for the delay effects. During low level flight, they

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will face additional risk due to their proximity to obstacles and a resulting decrease in their time to react and avoid collisions. Given the high accident rates, further research to investigate training strategies to offset delay effects clearly is necessary.

Visual Display Delay Effects on Pilot Performance

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WILDZUNAS RM, BARRON TL, WILEY RW. *Visual display delay effects on pilot performance.* Aviat Space Environ Med 1996; 67:214–21.

Background: The Helmet Integrated Display Sight System (HIDSS), originally proposed for the RAH-66 Comanche, displays sensor data from FLIR and image intensifiers, as well as flight instrument and targeting data. All these data will be processed through onboard computers before being displayed on miniature CRT's. In addition to processing delays, delays also are arising from the helmet tracker and from sensor slewing that may increase the total visual display delay to as much as 250 ms. ***Methods:*** Because display lag is one of the most important limitations affecting the ability of an aviator to use a display, we investigated the effects of 0, 67, 133, 267, 400, and 533 ms visual display delays on the flight performance of 10 volunteer U.S. Army aviators in a full motion flight simulator. ***Results:*** There were few performance decrements at 67, 133, or 267 ms delays as compared with the 0 ms delay condition. Significant performance decrements consistently were observed at 400 and 533 ms delays. ***Conclusions:*** Given the anticipated visual display delays for the proposed system, flight performance, as measured within the range of flight conditions and profiles examined, should not be affected significantly, although the aviators will experience an increase in workload to compensate for the delay effects. During low level flight, they will face additional risk due to their proximity to obstacles and a resulting decrease in their time to react and avoid collisions. Given the high accident rates, further research to investigate training strategies to offset delay effects clearly is necessary.

WHILE THE FUTURE DEVELOPMENT of the U.S. Army's RAH-66 Comanche helicopter remains uncertain, the technological advances being developed for the program should still have considerable value for use in current and future rotary-wing aircraft. One such advance now being examined for future rotary-wing systems is the Helmet Integrated Display Sight System (HIDSS). The HIDSS displays sensor information from forward looking infrared radar (FLIR) and image intensifiers, as well as flight instrument and targeting data. All these data are processed through onboard computers before being displayed on miniature helmet-mounted display devices. Although this system is intended to greatly enhance the pilot's ability to fly at night and in adverse weather, there are potential drawbacks. The current design for the HIDSS incorporates a visual display delay of 100 ms in presenting visual information to the pilot. Besides this processing delay, mechanical delays arising from the helmet tracker and from sensor slewing may increase the total visual display delay to as much as 250 ms. Thus, the display delays proposed for the system could result in the visual display lagging substantially behind the aircraft's actual motion.

Bryson and Fisher (5) have identified display lag as a critical limitation in affecting an aviator's ability to use a display, giving lag priority over other display characteristics. They concluded that visual display lags should yield errors in spatial location that are proportional to the amount of the visual display delay. Other research has suggested that adaptation to visual delay is related inversely to the amount of the visual delay and may not occur for delays beyond 300 ms (16). In addition, the visual display delays proposed for the HIDSS are in the range, and in the direction that could dispose some pilots to a condition not unlike "simulator sickness" which, in turn, may reduce the operator's performance and comfort (12–14,18). Research on the performance effects of display lag remains equivocal. In his review, Wickens (30) concluded that visual display delay as small as 40 ms can impair performance. Additionally, visual display delays near 100 ms have been found to degrade performance in a simulator (1,3,7,9,10,24,28) and to reduce overall system controllability (11). In contrast, visual display delays of approximately 150 ms have been found acceptable (4), and other investigators have reported that visual display delays near 250 ms are permissible (20–22,29). However, the level of allowable visual display delay may be reduced under conditions that require sequential, rapidly paced control inputs (25), as during nap-of-the-earth (NOE) flight, although the pilot probably can maintain performance at the expense of increased workload (2). Experimental findings bearing on this issue are summarized in **Table I.**

As Table I shows, performance in rotary-wing simulators may be more sensitive to visual display delay than performance in fixed-wing simulators, and more difficult tasks may be more sensitive to visual display delay than less difficult tasks. Accordingly, the literature on simulator visual display delays suggests that visual display delays near those proposed for the HIDSS may cause degradations in pilot performance.

The delays for this experiment were inserted into the

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TABLE I. VISUAL DISPLAY DELAY AND FLIGHT SIMULATOR PERFORMANCE RESULTS.

Report (ref.)	Aircraft Type	Task*	Outcome
Uliano, et al. (28)	Rotary-wing	Slalom maneuver	89 ms delay reduced performance
Cooper, et al. (7)	Fixed-wing	Carrier landing	100 ms delay changed pilot control behavior
Ricard, et al. (24)	Rotary-wing	Hover over ship	63 ms delay degraded performance 10%
Baron, et al. (2)	Rotary-wing	Fixed hover	132 ms delay reduced performance
Whitley and Lusk (29)	Fixed-wing	Sidestep landing	300 ms delay reduced performance
Crane (9)	Fixed-wing	Keep wings level	96 ms delay reduced performance
Miller and Riley (21)	Fixed-wing	Sinusoidal tracking	Break point in performance at 240 ms
Miller and Riley (22)	Fixed-wing	Sinusoidal tracking	Up to 250 ms delay acceptable
Lusk, et al. (20)	Fixed-wing	Maintain heading	300 ms delay reduced performance

* The reports are arranged in order of decreasing apparent task difficulty.

visual displays of a NUH-60 full motion flight simulator with the objectives of providing objective and subjective assessments of the effects of visual display delays near those proposed for the HIDSS on aviator performance. While the NUH-60 simulator's visual display is not a HIDSS, we feel that it provided a useful surrogate system for conducting a parametric investigation of the effects of visual display lags on aviator performance in a rotary-wing aircraft. In addition, simulation is safer than testing in actual aircraft and provides full field-of-view delay with a motion base—something HIDSS technology is not yet equipped to do. Therefore, the results obtained document the costs of the proposed visual display delays in terms of their potential effects on performance and safety of flight, and may help in developing performance requirements for future display systems.

METHODS

Subjects: This project was approved by the Human Use and Scientific Review Committees of the U.S. Army Aeromedical Research Laboratory (USAARL), Ft. Rucker, AL, and was monitored while in progress by an aviation research psychologist and USAARL's Flight Safety Office. Ten volunteer aviators (ages 23–35) were recruited as subjects. Although the recruitment announcement was not gender restrictive, all who volunteered were male. All subjects were current and qualified in the UH-60 and were familiar with the NUH-60 simulator. Informed consent was obtained from each subject.

Previous research at USAARL has employed similar numbers of aviators when measuring performance variables of the sort that are of interest in this experiment (6,26,27). Given the results of prior research and the repeated measure design of this experiment, a power analysis found that an alpha of 0.05 would yield a beta of approximately 0.01, with power equal to 0.9 for an effect size of one standard deviation. This analysis suggested that we should have a 90% probability of identifying a difference between means one standard deviation in size.

Instrumentation and apparatus: The experiment was conducted in USAARL's NUH-60 simulator. The simulator was "on motion" during all flights for this experiment. Air temperature during flights was maintained between 68–72°F, and relative humidity was maintained between 38–60%. The simulator's software load was modified to allow insertion of specified visual display delays into the simulator visuals. These visual display delay times were added to the system delays inherent in the simulator. The inherent or "phantom" delay for the simulator, 116 ms ± 16 ms, was determined by calculating the averages of 10 measurements. Thus, the total visual display delay (**Table II**) was the sum of the inherent delay and the experimentally inserted delay. However, given that the inherent delay was in the range of that found in the actual aircraft, only the added delay values are reported here.

Procedure: Subjects were briefed thoroughly by a rated aviator familiar with the mission profile. This individual also served as copilot-navigator on all flights. Following the briefing, subjects provided informed consent to participate in the experiment. Then, subjects practiced flying a standardized profile (**Table III**) with zero added delay until they reached asymptotic performance (three consecutive flights with no significant performance change on NOE altitude, downwind airspeed, and hover heading). This required 4 d of practice, on average.

For the experimental sessions, subjects flew the profile a total of 18 times (6 delays × 3 repeated trials). Each delay level was flown in a block of three trials, and the order of blocks was counterbalanced to offset any carryover or practice effects from previous levels. These flights were completed over 6 d (1 d for each block of the 6 delay levels). Each flight of the profile required approximately 45 min to complete, and each of the 6 test session days lasted approximately 3 h, with questionnaires administered between flights. Objective performance data (i.e., the degree to which the subject maintained the required standards for each maneuver) were sampled once per second during each flight by a VAX 780 and stored for subsequent analysis.

Because we expected a substantial amount of compensation by the subjects (i.e., a pilot compensating for poor aircraft handling qualities at the expense of increased workload), we solicited and collected subjective assess-

TABLE II. VISUAL DELAY LEVELS.

Added Delay	Inherent Delay	Total Delay
0	116	116
67	116	183
133	116	250
267	116	383
400	116	516
533	116	650

TABLE III. NUH-60 FLIGHT SIMULATION MISSION PROFILE.

Maneuver	Standard to Maintain
Traffic Pattern	
VMC Takeoff*	Maintain heading 350°, climb to 1000 ft. MSL.
Right standard rate turn (upwind to crosswind)	Turn from 350°–080°, altitude 1000 ft. MSL and airspeed 100 knots.
Straight-and-level flight (crosswind)	Maintain heading 080°, altitude 1000 ft. MSL and airspeed 100 knots.
Right standard rate turn (crosswind to downwind)	Turn from 080°–170°, altitude 1000 ft. MSL and airspeed 100 knots.
Straight-and-level flight (downwind)	Maintain heading 170°, altitude 1000 ft. MSL and airspeed 100 knots.
Right descending turn (downwind to base)	Maintain 500 $ft \cdot min^{-1}$ descent while turning from 170°–260°, descend from 100 ft. MSL to 800 ft. MSL.
VMC Approach	Maintain heading 350°, descend and land to specified area on runway.
Hover	Maintain heading 350°, altitude 10 ft. AGL, no drift.
Hover Turn	Maintain altitude 10 ft. AGL, rate of turn not to exceed $30° \cdot s^{-1}$, no drift.
Nap-of-the-Earth Flight	Maintain altitude 30 ft. AGL, airspeed 100 knots, heading as depicted on Global Positioning System (GPS) needle, avoiding obstacles.
Formation Flight	Maintain three rotor disk separation, at a 30° angle behind leadship (staggered left formation). Maintain leadship's altitude and airspeed.
Pinnacle Landing	Maintain heading 100°, descend and land to 1300 ft. MSL pinnacle.

* VMC (Visual Meteorological Conditions)

ment and questionnaire data. After each flight, subjects completed a Symptom Checklist (19), the NASA Task Load Index (TLX) (15), and the Handling Quality Rating Scale (HQRS) (8). The former addressed 16 symptoms related to motion sickness such as stomach awareness, blurred vision, sweating, dizziness, etc. Subjects rated the extent to which they experienced these symptoms from 1 (none) to 4 (severe). A single score was obtained for each flight by summing all the ratings. The NASA TLX recorded subjective taskload experienced within 6 domains (mental, physical, temporal, performance, effort, and frustration), along a continuum ranging from 1 (low) to 10 (high). In keeping with the suggestion of previous research (17,23), we weighted each subscale of the TLX equally.

The HQRS is a questionnaire that provided an overall subjective assessment of performance. This scale measured both the pilot's rating for the performance characteristics of the simulator, and the ease and precision with which he could perform the maneuvers. The rating scale ranged from 1 (excellent handling, highly desirable, pilot compensation not a factor for desired performance) to 10 (major deficiencies, control will be lost during some portion of operation). A rating of 5, near the midpoint, suggested that the delay level caused moderately objectionable shortcomings that required considerable pilot compensation for adequate performance. Subjects also were asked how much delay, if any, they perceived during the flight. This measure was rated from 1 (none noticed) to 5 (an excessive amount). Finally, a debriefing at the end of the simulator session allowed subjects to make any supplementary comments regarding the flight. After completing their simulator flights, subjects were advised to refrain from actual flight until the next duty day, in keeping with current guidelines to allow the dissipation of any possible symptoms of simulator sickness (4).

RESULTS

The objective performance data taken from the simulator are presented in **Fig. 1.** The magnitude of the score (% of 100) represents the degree to which the subject maintained the required standards for all maneuvers (Table III). The individual maneuver scores (not shown) are a composite taken from the various components required to perform the maneuver [e.g., NOE score = (airspeed score + altitude score + heading score)/3]. A visual examination of Fig. 1 reveals that increasing amounts of delay had an increasingly detrimental effect on flight performance.

The composite scores taken from each flight were subjected to a 6 (maneuver) × 6 (visual display delay) × 3 (trial) repeated measures analysis of variance (ANOVA). This analysis revealed significant main effects for maneuver [$F(5,54) = 76.63$, $p < 0.0001$] and for delay [$F(5,270) = 9.44$, $p < 0.0001$]. All remaining effects were nonsignificant [Tr, $F(2,108) = 0.86$, $p < 0.4281$; M × D, $F(25,270) = 0.96$, $p < 0.5240$; M × Tr, $F(10,108) = 1.10$, $p < 0.3711$;

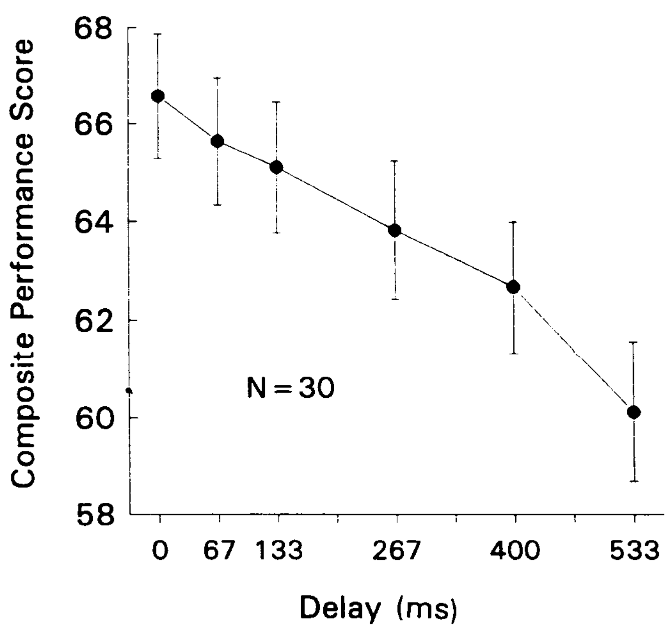

Fig. 1. Objective delay performance data taken from the NUH-60 flight simulator (collapsed across trials and maneuver).

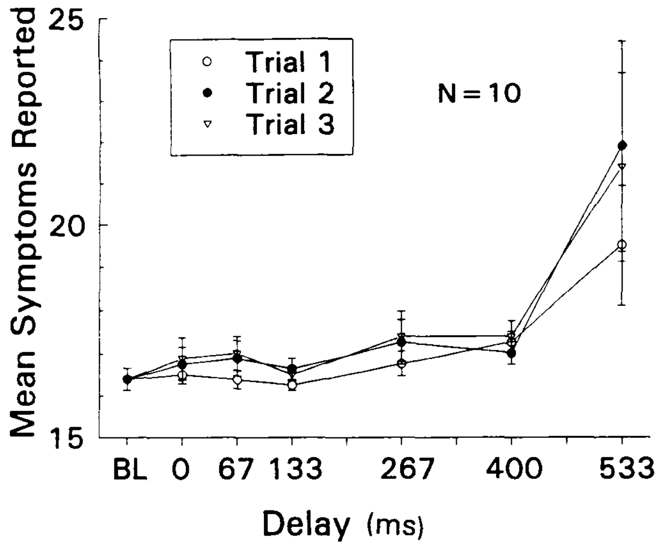

Fig. 2. Mean subjective response data taken from the symptomology questionnaire. Sixteen individual symptoms were rated according to the following scale: 1 = None, 2 = Slight, 3 = Moderate, and 4 = Severe. The ratings then were totaled. Higher mean scores suggest greater severity of motion related symptoms experienced during each of the delay conditions (minimum score = 16, maximum score = 64; BL = preflight baseline).

D × Tr, $F(10,540) = 0.57$, $p < 0.8363$; and M × D × Tr, $F(50,540) = 0.89$, $p < 0.6932$]. For the maneuver main effect, a Tukey HSD (Honest Significant Difference) post hoc comparison revealed that in general, subjects performed the 10-ft hover and 10-ft hover-turn significantly better than all other maneuvers, and performed the formation and pinnacle landing maneuvers significantly worse than all the others. A similar Tukey HSD comparison for the delay main effect revealed that subjects' performance, as compared with that in the 0 ms delay condition, was significantly lower at 400 and 533 ms of added delay.

The analyses of the subjective data (Symptom Checklist, NASA Task Load Index, and the Handling Qualities Rating Scale) were two factor repeated measure ANOVA's with repeated measures over delays and trials (including preflight baseline scores with the Symptom Checklist). For the Symptom Checklist, response data were recorded after each flight, and preflight reports of symptoms were used as a baseline. Higher total scores suggested greater severity of motion-related symptoms. These data, shown in **Fig. 2,** revealed significant main effects for delay [$F(6,54) = 3.73$, $p < 0.0035$] and trial [$F(2,18) = 4.05$, $p < 0.0354$]. In addition, there was a significant interaction between delay and trial [$F(12,108) = 2.13$, $p < 0.0203$]. A Tukey HSD comparison showed that discomfort symptoms reported after the longest delay condition (533 ms) were significantly greater than after all other flights, and that in particular, the symptoms reported after the second and third trials of that delay level were significantly greater than after the first trial.

In keeping with the suggestion of previous research (9,16), each subscale of the NASA TLX was weighted equally. Subjects rated taskload for 6 subscales (mental, physical, temporal, performance, effort, and frustration) along a continuum ranging from 1 (low) to 10 (high). Lower ratings suggested reduced taskload demand in that domain. The exception to this was the performance subscale, where low ratings suggested better subjective performance and high ratings reflected worse. Subscale ratings below the midpoint value of 5.5 were interpreted as relatively positive. The mean task ratings for each of the six delays are presented in **Fig. 3.** Overall, subjective taskload for each subscale appeared to have increased significantly during the two greatest levels of delay.

A 6 (task) × 6 (delay) × 3 (trial) repeated measures ANOVA was applied to the data. This revealed significant main effects for delay [$F(5,45) = 13.96$, $p < 0.0001$] and a significant two-way interaction for task × delay [$F(22,225) = 2.26$, $p < 0.0009$]. All remaining effects were nonsignificant [Ta, $F(5,45) = 0.57$, $p < 0.7218$; Tr, $F(2,18) = 3.26$, $p < 0.0618$; Ta × Tr, $F(10,90) = 0.98$, $p < 0.4622$; D × Tr, $F(10,90) = 0.31$, $p < 0.9763$; and Ta × D × Tr, $F(50,450) = 0.81$, $p < 0.8199$]. A Tukey HSD comparison showed that for the delay main effect, subjective taskload was significantly greater for the two longest delay levels (400 and 533 ms) than for the four shortest delay levels (0, 67, 133, 267 ms). However, taskloads were not significantly different between 400 and 533 ms delay levels. Tukey HSD results for the 2-way interaction between task and delay showed that in the longest delay condition, taskload for the mental and effort subscales was significantly greater than for the performance subscale, and that within the performance subscale, the 400 ms delay was not significantly different from the 67 and 267 ms delay levels.

The first part of the HQRS provides a measure of the pilot's rating for the performance characteristics of the simulator, the ease and precision with which the pilot could perform the maneuvers, and the amount of pilot compensation demanded for the required operations. These data, shown in **Fig. 4,** suggest that increases in delay result in poorer aircraft handling qualities and increased compensatory demands on the pilot.

These data were subjected to a 6 (delay) × 3 (trial) repeated measure ANOVA, which revealed a significant main effect for delay [$F(5,45) = 16.07$, $p < 0.0001$]. All remaining effects were nonsignificant [Tr, $F(2,18) = 0.22$, $p < 0.8017$; and D × Tr, $F(10,90) = 0.75$, $p < 0.6787$]. A Tukey HSD comparison for the delay main effect revealed that HQRS ratings were significantly greater at 400 and 533 ms of added delay, as compared with ratings in the other delay conditions.

The second section of the HQRS assessed the amount of delay perceived during each particular flight (**Fig 5**). A one-way ANOVA on these data revealed a significant main effect for delay [$F(5,45) = 27.99$, $p < 0.0001$], and the Tukey HSD comparison showed that subjects reported a significant increase in the amount of perceived delay during the 267, 400, and 533 ms delay conditions as compared with the lower delay conditions. There were no differences in reported perceived delay up to 133 ms.

In addition to the objective data recorded by the simulator computers and the subjective reports given by the pilot, the simulator operator kept a tally of the number of crashes during each flight. These data were important in that when the pilot crashed, the scoring routine in

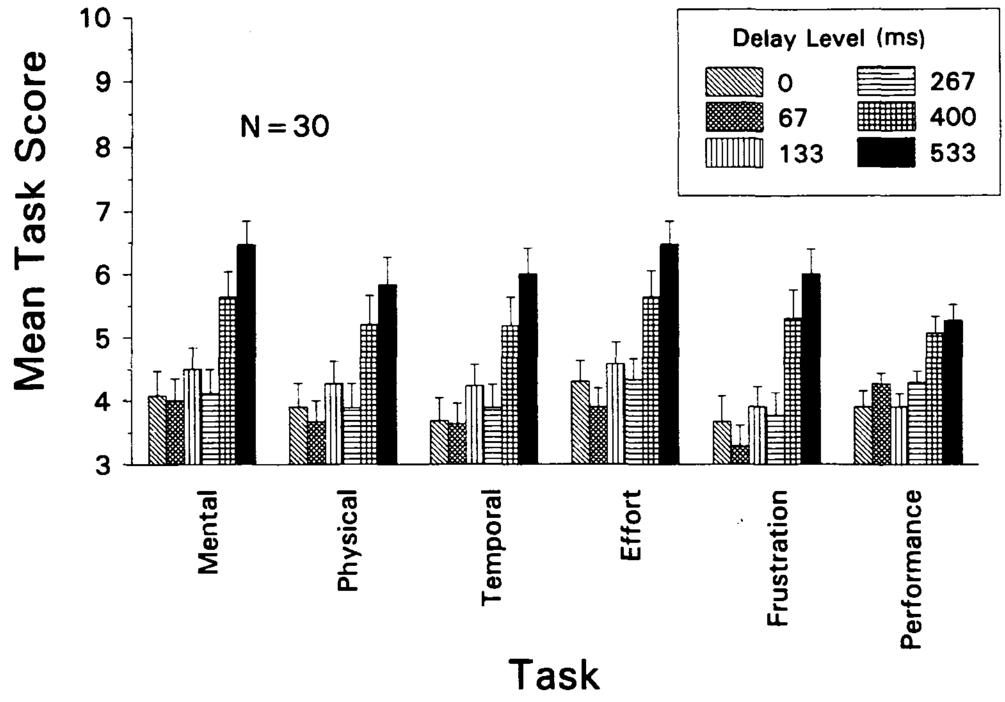

Fig. 3. Mean task scores for each subscale of the NASA Task Load Index (TLX) during each of the six delays.

the simulator stopped, and the operator had to reset the computer manually in order to complete the flight from where the crash occurred. (Crash data did not affect the overall composite score except that scores were deflated when pilots flew outside the prescribed parameters.) The data for the number of crashes recorded during each trial for each delay level are shown in **Fig. 6.**

These data were subjected to a 6 (maneuver) × 6 (delay) × 3 (trial) repeated measure ANOVA. This analysis revealed that all main effects and 2-way interactions were significant [M, $F(5,45) = 7.82$, $p < 0.0001$; D, $F(5,45) = 5.26$, $p < 0.0007$; T, $F(2,18) = 18.77$, $p < 0.0001$; M × D, $F(25,225) = 2.96$, $p < 0.0001$; M × T, $F(10,90) = 5.02$, $p < 0.0001$; and D × T, $F(10,90) = 2.66$, $p < 0.0068$]. Only the 3-way interaction between maneuver, trial, and delay was nonsignificant [$F(50,450) = 1.31$, $p < 0.0815$]. A Tukey HSD comparison showed that the number of crashes recorded during the 400 and 533 ms delay condition were significantly greater than during all other delay levels, and that in particular, these crashes occurred more often during the NOE segments than in all other segments of the flight. A practice effect was evident by a

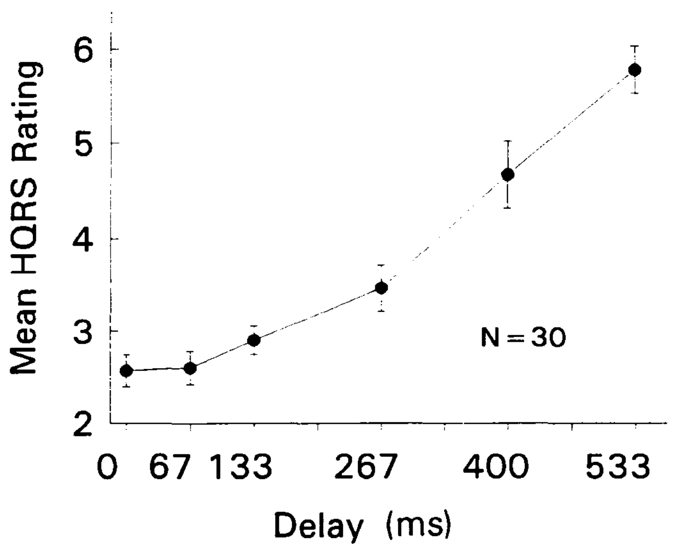

Fig. 4. Average ratings for the Handling Qualities Rating Scale (HQRS).

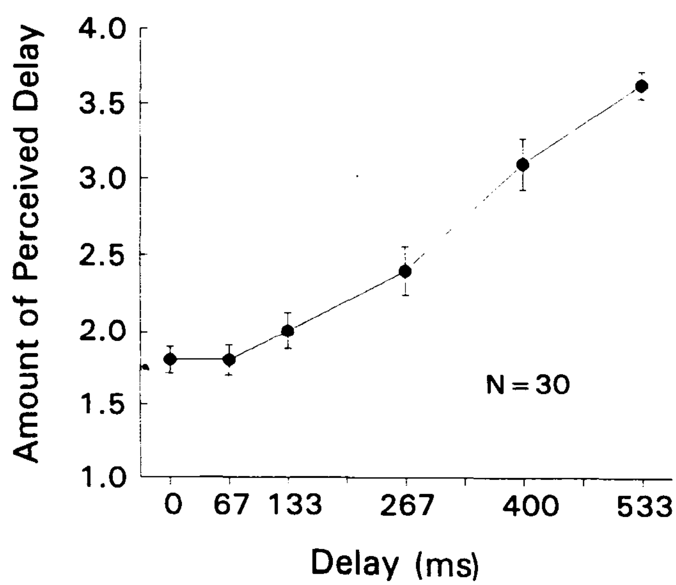

Fig. 5. The amount of perceptible delay, rated from 1 (none noticed) to 5 (an excessive amount), increased significantly for delay levels above 267 ms.

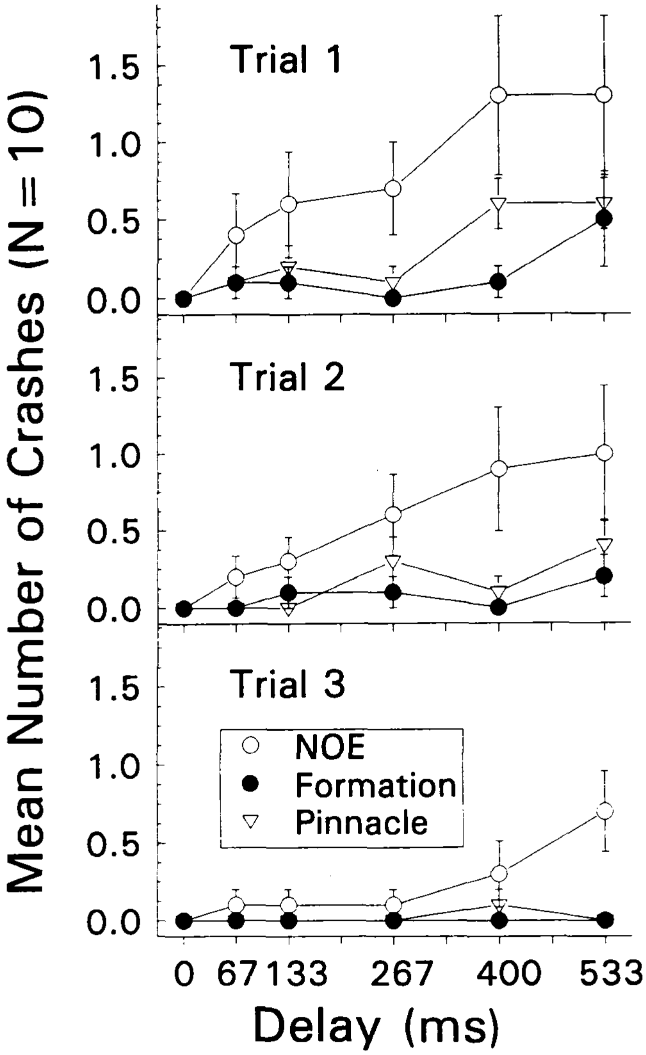

Fig. 6. Mean number of crashes recorded during each delay level broken down by trial and maneuver. No crashes were recorded for the traffic, or hovering maneuvers, and these data are not shown. In general, the number of crashes increased with increasing levels of delay. However, accident rates declined with practice as the number of trials increased.

significant reduction in crashes during the third trial as compared with the first two trials, particularly during the longer levels of delay.

DISCUSSION

The purpose of this experiment was to determine the effects of delays in visual display information on aviator performance. We inserted, through software modifications to a NUH-60 flight simulator, 0, 67, 133, 267, 400, and 533 ms of visual delay into the display system. Whereas display lag is one of the most important limitations affecting the ability of an aviator to use a display (5), these results could be used to help establish guidelines for allowable delays in image processing and enhancement systems currently being developed for military applications. Some of these proposed applications display sensor data from FLIR and image intensifiers, as well as flight instrument and targeting data. The processing delays, along with delays arising from the helmet tracker and from sensor slewing, could increase the total visual display delay to as much as 250 ms.

We found that visual display lags yielded errors that were proportional to the amount of the visual display delay. However, data from this experiment suggest that delays of 250 ms should not significantly affect flight performance. This agrees with other investigators who have reported that visual display delays near 250 ms are permissible (20–22,29). The finding that some maneuvers were performed better than others may reflect a difference in task difficulty. Interestingly, our data also suggest that the effects of delay may be equal for tasks of varying difficulty in that we failed to find an interaction between maneuver and delay.

Overall, the objective data for the delay effect in the simulator showed that aviators could perform all the required maneuvers with up to 267 ms of visual delay as well as they could in the 0 ms delay condition. However, there were significant decrements in performance at delay levels ≥400 ms. Although, since the maximum allowable delay for these maneuvers may actually lie between 267 and 400 ms, further research with smaller delay increments should be performed to determine precisely the maximum allowable display lag.

However, given the current data, we also found that subjects reported significant decrements in the handling qualities of the simulator that resulted in a need for greater compensation by the pilot at the two highest delay levels (400 and 533 ms). This increased demand on the pilot also was reflected in the increased reports of taskload at the two highest levels of delay. These results were consistent with the literature suggesting that increasing visual display lags may reduce the operator's performance and comfort (13) although the pilot probably can maintain performance at the expense of increased workload (2).

One plausible explanation for the performance decrement at high delay levels is that at these levels of delay, display lag is noticeable to the subject and that this induces motion sickness related symptoms that in turn adversely affect flight performance. These delays were in the range, and in the direction, to dispose some pilots to a condition not unlike "simulator sickness" (12,14,18). However, we discounted this argument given that subjects reported that delays ≥267 ms were significantly more perceptible to them, yet reported significant increases in motion sickness related symptoms only in the 533 ms delay condition.

Although there were no statistically significant performance decrements below 400 ms of delay, the operational significance of low levels of delay cannot be overlooked. Initially, the accident rates may appear low, but when converted to the standard measure of accidents per 100,000 h, these accident rates are several magnitudes above those seen in Army aviation. Even at 67 ms, the smallest inserted delay level, the calculated overall crash rate was 370 per 100,000 h. Based on U.S. Army Safety Center data, this is 170 times the Class A (major accident) average for the last 10 yr (2.13 accidents/100,000 h) and 90 times the worst-ever year on record (4.09 accidents/

100,000 h, established in 1973). That these high rates may be attributed to the visual delay is given by the observation that there were no crashes in the zero delay condition. In addition, there were no crashes in the traffic pattern, or the two hovering maneuvers, even at the 533 ms delay level. The majority of crashes recorded in this experiment occurred during the NOE segments. This is consistent with the literature (25) that states the allowable level of visual display delay is reduced under conditions like NOE flight that requires sequential, rapidly paced control inputs. However, it is noteworthy that during the debriefing sessions, pilots consistently expressed their opinion that they should have been able to modify their airspeed to offset delay effects, especially during low level flight. This is not unlike standard night vision device flight planning procedures that allow the pilot to tailor mission performance limits (e.g. airspeed) to adjust for environmental factors such as low ambient light levels.

The trial effect for the crash data also suggests that practice may offset the effect of delays, especially at the lower delay levels. In contrast to the first two trials, during the third trial, there were no accidents during the pinnacle landing maneuver until the 400 ms delay level, and none during the formation flight at any delay level (Fig 6). NOE accidents during the third trial were reduced 70% and 55%, when compared with the first and second trials, respectively, with the largest reductions occurring at the lower levels of delay. This supports previous research suggesting that adaptation to visual delay may be inversely related to the amount of the visual delay (16). However, it also contrasts with the finding that adaptation may be nonexistent for delays beyond 300 ms (16). The significant reduction in accidents during the third trial across all delay levels suggests that pilots were adapting to even the longest delays. Although further research is necessary, it is not improbable to speculate that given more practice with the longer delay levels, pilots would overcome the delay effects and pilotage scores would increase.

Provided with all these results, we conclude that display delays up to 250 ms are permissible although the aviator will experience an increase in workload to compensate for the delay effects. During low level (nap-of-the-earth) flight, they will face some additional risk due to their proximity to obstacles and a resulting decrease in their available time to react and avoid collisions. Given the anticipated visual display delays for the proposed HIDSS system in the RAH-66 Comanche, flight performance, as measured within the range of flight conditions and profiles examined, should not be affected significantly. However, given the severe operational effects of display lag (i.e., increased accident rates during low level flight), further research to investigate effective training strategies to offset delay effects clearly is necessary.

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The opinions, interpretations, conclusions and recommendations are those of the authors and not necessarily endorsed by the U.S. Army.

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References to USAARL reports have unlimited distribution and can be obtained readily by all readers from the primary author upon request.

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