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Time Delays in Visually Coupled Systems During Flight Test and Simulation

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Increasing control system time delays have well-documented detrimental effects on pilot-in-the-loop performance. With increased use of helmet-mounted displays in aircraft, pilots may soon be exposed to both control system and visual display system time delays. They may be sensitive to both the magnitude and source of the time delay, that is, some pilots may be more sensitive to visual delays than to control delays, or vice versa. In the current study, control and visual delays were examined in two experiments, the first conducted in a helicopter and the second conducted in a flight simulator. A helmet-mounted display was used to present external imagery and symbology in both experiments. Standardized low-level maneuvering tasks were used to examine changes in system handling qualities ratings as a function of time delays in the control and visual display processing loops. The addition of delays in both the control and the visual loops impaired the system handling qualities and increased the magnitude of position maintenance error. Differences between control and visual delays were evident in reports of motion sickness symptoms, which were more frequent for visual delay conditions. Motion sickness symptoms and related physiological effects induced by delays may increase pilot fatigue. Therefore, determination of acceptable latency criteria for design and implementation in systems with visually coupled components is critical.

Nomenclature

t	=	time, s
θ	=	phase angle, rad
$\Delta\tau_{\text{program control}}$	=	programmable digital time delay, s
$\Delta\tau_{\text{program visual}}$	=	programmable video delay of the camera image, s
τ	=	time delay, s
$\tau_{\text{eff helo}}$	=	helicopter effective control system time delay, s
$\tau_{\text{eff platform}}$	=	the effective time delay of the dynamic response of the camera platform to head motion, s
$\tau_{\text{eff visual}}$	=	total visual time delay, s

Introduction

As a rule, time delay in a control system degrades operator performance[1] in a wide variety of systems ranging from neuroprostheses[2] to aircraft control systems.[3] In any system, the effects of delay on task performance vary with changes in the task demands, system dynamics, and operator control strategy. Moreover, operators may be sensitive to both the magnitude and source of the delay in complex nonlinear systems. For example, time delays in the visual feedback loop or control loop of the aircraft will adversely affect performance, but visual delays may elicit additional physiological symptoms that can have a detrimental effect on the pilot. From a safety and efficiency perspective, it is becoming more important to identify delay sources and minimize their effects on operator performance.

Modern visually coupled display systems have introduced two types of visual delay to pilots: delays due to computer processing, which are usually transmission delays, and effective delays due to dynamic (mechanical) system lags. Briefly, transmission delays ($e^{-\tau_s}$) represent a delay in the transmission of a signal that does not change any other characteristic of the signal. In contrast, exponential lags $[1/(\tau_s + 1)]$ may result in an effective time delay that affects the operator. In the systems tested for this paper, the baseline helicopter and camera platform dynamics were treated as exponential lags, whereas the added programmable visual and control delays were treated as transmission delays (Fig. 1).

Figure 1 shows a simplified model (based on the structural isomorphic model[4]) of a pilot in a helicopter-borne visually coupled system. It shows delays in both the control loop (the transmission delay $\Delta\tau_{\text{program control}}$ and the exponential lag $\tau_{\text{helicopter}}$) and the visual feedback loop (the transmission delay $\Delta\tau_{\text{program visual}}$ and the effective time delay $\tau_{\text{eff platform}}$) that were representative of the delays we investigated. Note that these delays are often an additive combination of exponential lags and transmission delays. Examining the system, one can see that the vestibular and visual systems are equally affected by the control system time delay. However, only the visual feedback path is affected by the camera platform dynamics and the programmable visual delay. This model can serve as a starting point for the comparison of the effects of visual delays to the effects of control delays on performance. Note from Fig. 1 that the control system time delay is represented by $\tau_{\text{eff}_{\text{helo}}}$ and comprises the inherent system time delay (156 ms) and a programmable digital time delay $\Delta\tau_{\text{program control}}$. The total visual delay $\tau_{\text{eff}_{\text{visual}}}$ comprises the time delay inherent in the dynamic response of the camera platform to head motion $\tau_{\text{eff}_{\text{platform}}}$ (50 ms) and the programmable video delay of the camera image $\Delta\tau_{\text{program visual}}$. There is a long history of

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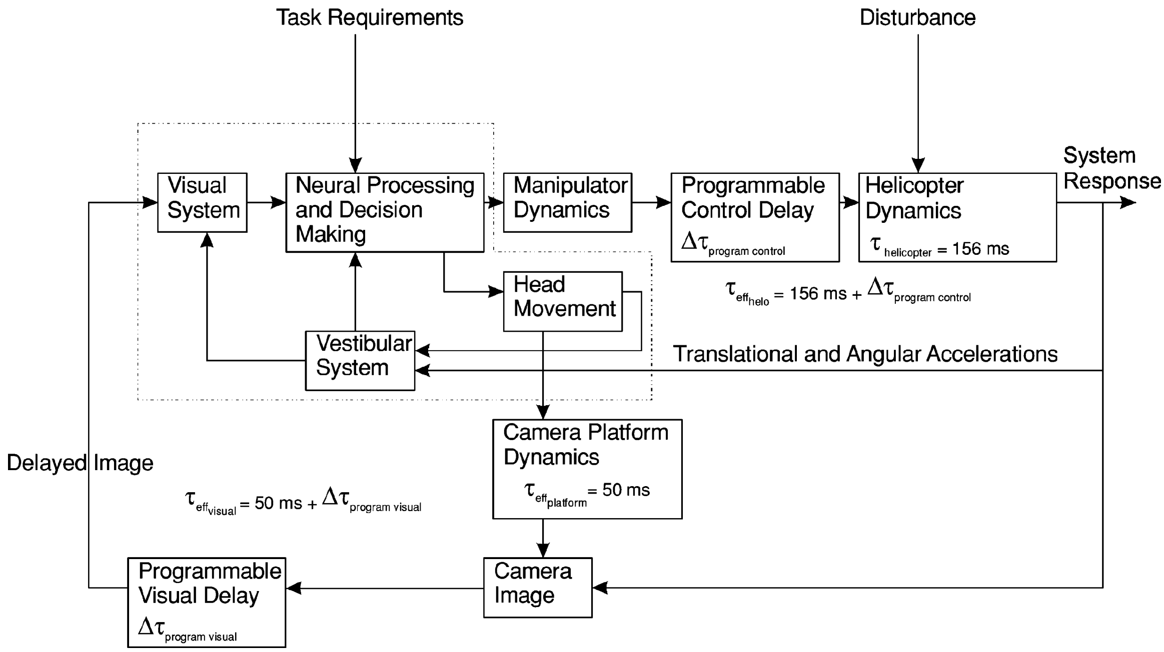

Fig. 1 Modified feedback model of pilot control.

research into the effects of time delays, involving both complex and simple systems. Numerous manual tracking studies have confirmed that control performance degrades in the presence of increasing system time delay.[5–8] Early researchers[5,8] showed that the addition of small amounts of exponential lag degraded compensatory tracking performance in a simple system. Tracking deteriorated with imperceptibly small delay levels (40 ms) and the tracking error grew as the delay increased. The findings from these early studies are aptly summarized by the statement, "System lags in general are harmful to performance."[1]

As system complexity increases, for example, when lags or delays are added to the system that relates lateral cyclic force to helicopter roll angle, or when faster or higher-frequency tracking is required, delays harm performance. As delay increases, feedback of the effect of a control input to the pilot is delayed. This can lead to an oscillatory pattern of increasingly exaggerated control inputs known as pilot-induced oscillation (PIO) where the pilot can eventually lose control of the system.[9]

With practice, pilots adjust to delays by modifying their control inputs. Pilots will reduce their control bandwidth[10] or use a low bandpass filtering strategy to deal with PIO arising from control system time delays. Alternatively, they may add a lead term to their control inputs.[11] Some pilot techniques are more vulnerable to the effects of time delay.[12] Likewise, some maneuvers are more affected by time delays than others[13] are. Unfortunately, some time delays exceed the pilots capacity to adapt. Time delays were identified as significant contributors to problems with the pitch control of the F-18A, the Tornado, the YF-17 (Ref. 14), and the space shuttle.[15] One of the primary factors contributing to the space shuttle pitch axis PIO was a long effective time delay (0.5 s) between the pilot's pitch control inputs and the detection of a pitch attitude change of the orbiter.

Compared to the volume of research on control delays, the effects of visual time delay in flight are relatively unexplored. This may change as synthetic vision systems and visually coupled systems enter more widespread use. Visually coupled helmet-mounted display (HMD) systems are in use or proposed for use on a variety of attack and scout helicopters, including the Apache, Comanche, and Tiger.[16] Any of these systems may have significant delays in their visual path, typically the result of image capture, image enhancement, image generation, image display, head tracking, and/or sensor platform dynamics.

Although there are not a great deal of flight-test data available on visual delays, they have been explored in aircraft simulators. Tests on simple visual systems such as head up display symbology have shown that as little as 70 ms caused observable subjective performance decrements on precision glideslope approaches.[17] Others have reported decreasing tracking performance with increasing delays (0, 80, 200, and 300 ms) between visual imagery display and synchronous motion.[18] A summary of time delay studies[19] showed that time delay in the visual imaging system of a simulator reduced pilot performance and changed pilot control behavior. Three of the reviewed studies on rotorcraft simulation[19] showed reductions in performance at visual time delays of 63, 89, and 132 ms beyond the baseline time delay. Performance degradation was observable with as little as 67 ms of added delay, even though the delay was not felt by the pilots to be excessive. However, the authors[19] concluded from their data that delays up to 250 ms are acceptable for rotorcraft, and pilots can adapt to the visual delays.

From these studies, one can observe detrimental effects from visual delays on objective measures of pilot performance. However, there are differing opinions on the amount of visual delay that is acceptable before performance becomes impeded. This may be due to the different systems, pilots, and tasks used in the studies. As discussed earlier, as the gain of maneuvers increases or the precision requirements associated with a task increases, lags or delays that were apparently acceptable can become problematic.[15]

In addition to the objective performance decrements, there is evidence of physiological effects related to time delays in the literature on simulator sickness, that is, motion-sicknesslike symptoms that are encountered in simulators or virtual environments. Increases in reports of simulator sickness have been linked to visual delay increases.[20] The commonly accepted "sensory conflict" theory holds that delayed simulator visuals may introduce a mismatch between the visual and vestibular experiences of orientation and could generate disorientation or motion sickness symptoms.[21] Failure to resolve mismatches between visual and vestibular orientation signals may generate a range of symptoms from fatigue through disorientation to nausea.[22] These physiological symptoms may reduce the pilot's capacity to adjust to increasing workload and maintain situation awareness, as well as affecting performance directly. The magnitude of the sensory conflict may influence the number and severity of symptoms, with smaller conflicts eliciting fewer and milder symptoms. For example, two studies[23,24] found few changes in symptoms at latencies lower than 250 ms, whereas other investigators[19] noted a marked increase in the reports of simulator sickness during their study when using delays of more than 650 ms.

We have seen from the previous work that control and visual delays degrade performance and that visual delays may also have an impact on simulator sickness. However, there does not seem to be consistent agreement on what levels of delay are acceptable. The magnitude of delay that affects performance and elicits physiological symptoms may vary greatly because of task demands, system dynamics, visual scene parameters, control strategies, and pilot susceptibility. We decided to have a closer look at some of these issues surrounding visual and control delays in two experiments: one in the National Research Council of Canada (NRC) Bell 205 helicopter, and one in a flight simulator modeling the NRC Bell 205 at the University of Toronto Institute for Aerospace Studies (UTIAS).

Experiment 1: Flight Trials

The first investigation was conducted to determine the effects of visual time delays on helicopter handling qualities ratings and to compare these with the effects of control system time delays. In this experiment, we wanted to examine two hypotheses:

1) Based on the feedback model of pilot control, both visual delay and control delay would degrade handling qualities.

2) Because of disorientation and motion sickness, visual time delay will have greater performance effects than control delays.

Participants

Three qualified test pilots participated in the experiment, and their relevant flight experience is outlined in Table 1. HMD hours includes hours flown while using night vision goggles (NVG).

Equipment

The tests were flown on a highly modified Bell 205 helicopter, as shown in Fig. 2, equipped with a sophisticated data recording and analysis system. The NRC Bell 205 is a fly-by-wire variable stability platform for in-flight simulation of other aircraft, in-flight investigation of control system characteristics, cockpit systems development, and data generation for advanced aircraft specifications. The Bell 205 was configured with a rate-damped control system incorporating interaxis decoupling that was representative of current helicopter control systems. The system bandwidths were 3.5 rad/s in roll, 2 rad/s in pitch and 2 rad/s in yaw based on ADS-33D (Ref. 25) small amplitude criteria. These meet the level 1 criteria for a utility helicopter. The visually coupled system installed in the helicopter consisted of four main elements: a mechanical head tracker, an HMD, a camera platform, and a set of cameras. The HMD system (Fig. 3), supplied by CAE, Inc., displayed stereo video images from the externally mounted cameras and is described elsewhere[26] in more detail. The camera platform system maintained the camera line of sight parallel to the pilot's line of sight based on head movement and position data from a mechanical tracking system. The cameras were mounted on a camera platform, a hydraulically operated gimbal with three rotational degrees-of-freedom. The HMD system in the test configuration provided a partially overlapped binocular image, with a design-eye position corresponding to the camera location, that is, on the roof of the aircraft. The see-through capability of the HMD optics was suppressed by fitting an opaque visor.

A digital image processing unit (DIPU), supplied and programmed by CMC Electronics Canada, Ltd., was inserted in the video stream between the cameras and projection system to add variable amounts of transmission delay to the video signal (as outlined in Table 2). The total visual delay included the transmission delay from the DIPU and the effective time delay due to the camera platform dynamics, which are described elsewhere.[27] The effective time delay of the camera platform dynamics, from a head tracker step input to a camera platform movement, was determined as 50 ms with a time domain technique.[28] The camera platform dynamics vary slightly in each of the pitch, roll, and yaw axes. For the sake of simplicity in calculation and analysis, the yaw time delay (50 ms) was used to represent all three axes. The programmable visual delay varied from 50 to 346 ms.

The baseline control delays were obtained from a six-degree-of-freedom 6 DOF rigid-body-model.[29,30] A control input time delay

Table 1 Pilot qualifications for experiment 1

Pilot	Age	Total hours	Helicopter hours	NVG/HMD hours
1	35	2850	2600	40
2	35	4100	2900	40
3	55	10000	2000	30

Table 2 Experiment 1 conditions (delays in ms)

Control delay	Visual delay (camera platform plus programmable video delay) 50	107	144	207	346
156	Block 1	Block 2	Block 2	Block 2	Block 2
316	Block 1	——	——	——	——
460	Block 1	——	——	——	——

Fig. 3 NRC visually Coupled system.

Fig. 2 NRC Bell 205.

Table 3 Mirror C performance tolerances

Performance	Desired	Adequate	DVE desired	DVE adequate
Lateral Position during forward flight, ft	±10	±20	±10	±20
Altitude 20-ft AGL, ft	±10	<50	±15	<60
Heading during forward flight, deg	±10	±15	±10	±15
Time limit to complete translation, s	45	60	60	90
Time limit to achieve hover, s	5	10	10	20

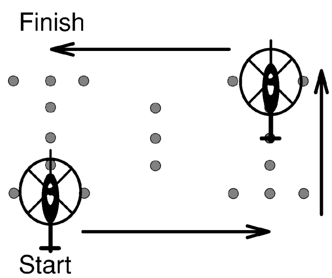

Fig. 4 Cone and course layout for the mirror C.

was used to approximate the effects of rotor and control actuator dynamics. Based on this model, the inherent control delays of the NRC Bell 205 were different for each of the four control paths, lateral cyclic, longitudinal cyclic, collective, and pedals. Because most of the pilot's control activity occurred on the lateral and longitudinal cyclic, all control delays were considered equivalent to the cyclic control delays of 156 ms. This greatly simplified data analysis. Programmable control delay could be inserted simultaneously into all four paths of the fly-by-wire control system. The delays were multiples of the flight-control system sampling interval (15.67 ms) and were set at three levels: baseline (156 ms), intermediate (316 ms), and long (460 ms).

Procedures

Pilots flew the mirror C and sidestep maneuvers with a variety of control system and video system delays[31] as shown in Table 2. Handling-qualities ratings[32] and motion sickness data were collected. Structured debrief sessions were held after each flight.

Pilots flew a series of training and familiarization flights to obtain a consistent level of performance before beginning the evaluation flights. There were two to three evaluation flights, blocked by delay type (control or visual). Conditions with the same block number were tested in the same flight. Within each flight, the trials were blocked by maneuver (side-step or mirror C), and the pilot was exposed to the delays in a randomized sequence. A pilot could complete approximately one block, for example all control delay conditions in a flight. Pilots followed the ADS-33D (Ref. 25) procedure, whereby they practiced a maneuver at each delay condition until a consistent level of performance was obtained, following which the maneuver was rated.

The sidestep was selected as an aggressive control input task, whereas the mirror C was developed as a task that required precise handling and large head movements. The sidestep was performed in accordance with ADS-33D (Ref. 25) performance standards. The mirror C, (Fig. 4 and Table 3), was specifically constructed for this investigation. Pilots often maintain a relatively fixed head position to counter the effects of delays. The mirror C was developed to compel pilot to make large head movements to better examine delays in the head tracking and lags in the sensor platform dynamics. The maneuver began from a stabilized hover and the pilot initiated a lateral transition to the right along the sidestep course. At the course endpoint, they flew forward, then initiated a final lateral transition to the left. Pilots maintained a constant helicopter heading throughout the maneuver. The performance criteria for degraded visual environments were used in deference to the visual limitations of the HMD.[26] Trials were flown with winds less than 10 kn (18.52 km/h) on clear and cloudless days to ensure that environmental conditions were consistent for each flight. Bright and sunny flight conditions were required for good HMD image contrast over the snow-covered test course.

Results

Handling Qualities

The handling qualities of the aircraft were evaluated using the Cooper–Harper handling qualities rating (HQR) scale.[32] Handling qualities are influenced by the vehicle dynamics, the disturbance characteristics, the task demands, and the pilot's ability to perceive the environment. There was a tendency for the HQRs to increase with increasing amounts of either control or visual delay. The increase in ratings from HQR 5 to HQR 7 (Fig. 5) reflected the higher workload required to maintain adequate task performance. This trend was apparent for visual and control delays, as shown in Fig. 5. With shorter time delays (<150 ms), handling qualities were consistently rated as level 2. With longer time delays, the ratings increased by 1.5 or 2 HQRs, generally from level 2 to level 3. The transition in HQRs from level 2 to level 3 in this instance reflected a change from adequate to subadequate task performance (HQR 5–6 to HQR 7).

In contrast to the literature on the effects of delays on flight performance, there were few reports of PIO. In the longer visual delay conditions (207 and 346 ms), two pilots reported that they were on the edge of PIO. The third pilot noted that the longest visual delay made the helicopter "feel wobbly, but that this was not a PIO situation." There was only one instance (460 ms control delay, mirror C) where the safety pilot had to take control of the aircraft because the evaluation pilot was unable to continue safely. All of the pilots tested in experiment 1 had extensive prior exposure to control delays from other experiments. They all indicated that they could readily adapt their strategy for dealing with control delays to trials where they encountered visual delays. They reduced the aggressiveness of their control inputs, that is, used a low gain control strategy, to cope with the time delays.

Visual Delays vs Control Delays

It is difficult to ascertain any differences in handling qualities between the effect of control and visual delays from examination of the Cooper–Harper data. There does not appear to be a large difference in the extent to which performance was impaired. For the sidestep, visual time delays appeared to degrade performance slightly more than the control time delays. For the mirror C, the results did not show an overall trend of either control or visual delays being more detrimental. The amount of delay impairing performance changed among the tasks. Handling qualities worsened rapidly in the region of 144–207 ms of visual delay and then tended to level off. Control delays tended to produce gradually increasing performance deficits with increasing amounts of delay.

Few motion sickness symptoms were reported during flight. All four instances reported occurred in the mirror C, with two of the reports occurring in the control delay conditions and the remaining two reports occurring in visual delay conditions. Note that the symptoms were reported during a maneuver designed to force head movements. There was one notable difference between the control and visual delay conditions. Two pilots reported postflight discomfort following exposure to the visual delay conditions that lasted for the remainder of the day, suggesting that subtle physiological changes may be happening in response to the long visual delays. The simulator sickness literature indicates that symptoms may, in some cases, persist long after exposure, and may require a night's sleep for full recovery.[33] The U.S. Navy field manual on simulator sickness[34] recommends that pilots who develop simulator sickness not fly the remainder of the day.

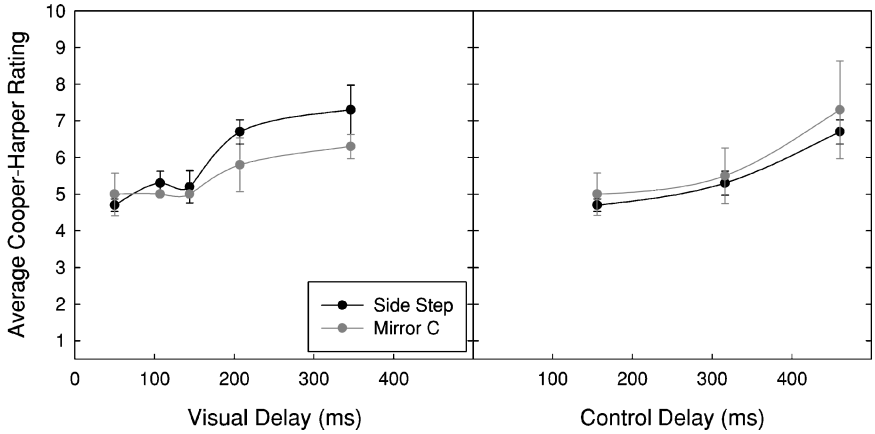

Fig. 5 Effect of time delays.

Time Delay and Task Interactions

Cooper–Harper ratings for the delay conditions in the mirror C and sidestep tasks were roughly equivalent, although the tasks vary widely in aggressiveness. With short delays (<150 ms), ratings of HQR from 4 to 6 were given for all maneuvers, whereas the longest delays elicited ratings of HQR 6 to 10. At some point, all maneuvers required the pilot to hover the aircraft, which turned out to be a demanding task in the presence of time delays. In both the sidestep and the mirror C the pilot was required to stabilize the helicopter in a low gain hover at the end of the dynamic maneuver. During the debriefing, each pilot indicated that the most difficult part of any of the maneuvers was the stabilization of the hover portion of the maneuver. The pilots also commented that, in achieving the hover, they are required to control the helicopter precisely in all three axes (vertical, longitudinal, and lateral), whereas during the translations, only two axes are tightly controlled. The precision required to maintain a designated position drives up the pilot's gain, exacerbating the effects of time delays.

Discussion of Experiment 1

This experiment showed that delays in the control loop or the visual loop impaired pilot performance in flight, supporting our first hypothesis. With delays in the control system, the response to the control input is delayed, but once the helicopter moves, the pilot can immediately detect the helicopter response, as can be predicted from the model in Fig. 1. Conversely, with delays in the visual loop, the helicopter response is (nearly) immediate, but detection of the response in the visual channel is delayed. Pilot control strategy to compensate for these delays tended to be low gain, with infrequent control inputs to back out of the loop. As a result of this strategy, and the delays, the handling qualities of the pilot/helicopter system degraded and pilot workload increased.

At the beginning of the experiment, a performance difference was expected between equivalent control and visual delays (hypothesis two). The handling quality data do not show sufficient differences to support this hypothesis. It appears that approximately equal decrements in handling qualities were observed between control and visual delay conditions. However, the long visual delay conditions produced some reports of postflight motion sickness symptoms, which lasted for the remainder of the day. Although the pilots did not have any previous experience with visual delays in flight, they were able to deal with the visual delays by modifying existing strategies for control delays. To deal specifically with visual delays, the pilots again[26] reported that they tended to reduce the number of large head movements, especially in yaw. The pilots reported that large yaw head movements increased disorientation and workload.

Three aspects of experiment 1 warranted further examination. First, pilots identified the hover component of all tasks as difficult, and so we decided to examine the effects of time delays on performance of a standardized hover task, the ADS-33D hover in the simulator trials of experiment 2. The ADS-33D hover task performance is driven by high gain control movements in all axes to maintain precise positioning and should, therefore, be affected by time delays.

Fig. 6 Motion base simulator at the university of toronto institute for aerospace studies.

Second, there were few reports of motion sickness symptoms, but there were reports of postflight discomfort. We were intrigued by these reports and felt that they may be showing evidence of physiological effects that were not immediately noticeable during tests but that may have affected performance. It was felt that further investigation was warranted.

Third, the effects of the delays in experiment 1 were not as detrimental to performance as the literature suggested. For example, pilots in another study[13] experienced PIO with smaller (190 ms) control delays than were used in the current study. Indeed, in that study longer time delays were not tested in the more demanding tasks because of safety concerns. Some of the difference between the studies may be attributed to the different aircraft and maneuvers used. In the current study, the investigators attributed the lack of the most detrimental delay effects to the benign atmospheric conditions required for test performance (winds <10 kn as per ADS-33D) and unique pilot adaptation strategies. The presence of more turbulent atmospheric conditions will introduce disturbance inputs to the system that degrade the effectiveness of a predictive control strategy. A higher gain closed-loop strategy would be required to maintain performance criteria for the maneuvers. However, the higher gain control inputs required to deal with the turbulence are contradictory to the strategy required to deal with the time delay. Thus, the time delays effects may be pronounced in the presence of turbulence and gusting winds. These issues were examined in experiment 2.

Experiment 2: Simulator Trials

We examined visual delays (similar in magnitude to experiment 1) under controlled conditions in a research flight simulator with a motion base at UTIAS (Fig. 6). The flight simulator was equipped with an HMD system similar to the HMD used in experiment 1. The flight model[27] used in the simulator was based on the flight control laws of the B205 research aircraft. Turbulence was introduced in the simulator to add disturbances in the vehicle response that would counter the pilot compensation strategies adopted by pilots in the flight trials. We examined the following hypotheses:

1) Pilot performance of the hover maneuver would be affected by visual and control delays.

2) There would be a greater tendency for motion sickness in the visual delay conditions.

3) The presence of turbulence would degrade handling qualities.

Participants

Two qualified experimental test pilots and one line pilot participated in the study. Their relevant flight experience is listed in Table 4. Two of the pilots had participated in experiment 1, whereas the third pilot had little experience with time delays and with HMDs.

Equipment

The tests were flown on the UTIAS research simulator with the flight model and flight controls for a Bell 205 medium transport helicopter.[35] It was configured with a rate-damped control system incorporating interaxis decoupling. The flight controls were sampled and the flight equations solved at a rate of 60 Hz. The cockpit was mounted on a 6 DOF motion platform capable of translational (surge, sway, and heave) and rotational (yaw, pitch, and roll) motion.

In the UTIAS system, a magnetic head tracker measured the pilots head movements. A computer image generator used the head position and orientation information to generate an image of the simulator database. External imagery and flight symbology were presented on an built by CAE, Ltd. The HMD system (as tested) displayed a binocular, color image, with see-through retained (the relevant parameters are listed in Table 5). The simulator handling qualities were rated as level 2.

The simulator motion base was a CAE Series 300 hexapod with 6 DOF that utilized 3-ft stroke hydraulic actuators incorporating hydrostatic bearings. It had approximately ±0.6-m maximum travel in the linear degrees of freedom and ±22-deg maximum travel in the angular degrees of freedom. It was capable of ±1-g maximum acceleration in the linear degrees of freedom and ±1-rad/s maximum velocity in the angular degrees of freedom. The effective hardware time delay was 69 ms (Ref. 36). When the NRC Bell 205 was simulated, the motion input scaling on all degrees of freedom was 0.5 (Ref. 37). Each axis had some degree of filtering, and both high-pass and low-pass second-order filters used a damping ratio of $\zeta = 1.0$. The high-pass filters all had transfer functions with numerators of s^n where n is the order of the filter. The low-pass filters all had transfer functions with numerators of ω_m^n, where n is the order of the filter and ω_m is the undamped natural frequency. The x (surge) high-pass filter was second order with an undamped natural frequency of 1.67 rad/s. The y (sway) high-pass filter was second order with an undamped natural frequency of 1.94 rad/s. The z (heave) high-pass filter was third order, made up of a second-order filter having an undamped natural frequency of 3.91 rad/s in series with a first-order filter having a break frequency of 0.2 rad/s. The pitch and roll high-pass filters were first order with a break frequency of 0.39 rad/s. The yaw high-pass filter was second order, made up of a first-order filter having a break frequency of 0.78 rad/s in series with another first-order filter having a break frequency of 0.2 rad/s. The low-pass pitch tilt-coordination filter was second-order with an undamped natural frequency of 1.17 rad/s. The low-pass roll tilt-coordination filter was second order with an undamped natural frequency of 1.67 rad/s.

Procedure

In this experiment, each of three pilots carried out a hover in the simulator while encountering four levels of time delay and three turbulence conditions. Each pilot flew a series of precision hover maneuvers in accordance with ADS-33D degraded visual environment (DVE) performance standards, with one important exception. The pilots were not required to transition to the hover location, and they began the maneuver in a designated position at the center of the hover area. The displayed simulator test course was based on scenery and landmarks from the actual flight-test course at the NRC Flight Research Laboratory.

Pilots flew a series of training trials, and when they reached a consistent level of performance, they began the evaluation trials. A counterbalanced series of visual delays and turbulence levels were presented to the pilot. The pilot repeated the hover maneuver in each time delay condition until a consistent level of performance was obtained and then rated it.

The four levels of time delays (67, 134, 184, and 334 ms) added to the visual display were based on those used in experiment 1. The visual delay was a multiple of the 60-Hz display refresh rate, which was the same as the control sampling rate. The visual delay was implemented by the delay of the output of the computer that solved the flight equations before the output was sent to the image generator. The motion base and instrumentation responded in a normal way, without delays. The control delays (85, 162, 212, and 362 ms) were implemented through the control inputs being buffered before they were used in the model computations. This delayed both motion and visual responses, simulating the control delays used in experiment 1.

Three levels of turbulence (as shown in Table 6) were chosen to provide the pilots with reasonable magnitude, but unpredictable

Table 4 Pilot qualifications for experiment 2

Pilot	Age	Total hours	Helicopter hours	NVG/HMD hours
1	35	2950	2700	60
2	35	4225	3000	60
3	37	6000	1800	5

Table 6 Experimental turbulence parameters

Turbulence level	Average wind speed, kn	Gust magnitude, kn
No turbulence	10	0
Moderate turbulence	10	±1.2
Maximum turbulence	10	±2.4

Table 5 Comparison of NRC bell 205 visually coupled system and UTIAS simulator

Parameter	UTIAS Simulator	NRC 205 Helicopter
Head tracker	Polhemus magnetic	Mechanical
Monocular field of view (FOV)	46 H × 36 V	62.5 × 40
FOV overlap, deg	21	25
Total FOV, deg	71 × 36	100 × 40
Image source	MaxVue Enhanced B image generator	NTSC video cameras on a gimbaled platform
Display resolution	1180 × 1056	754 × 485
Vertical resolution	1.9 arc min/pixel pair	2.5 arc min/pixel pair
Motion cuing	6 DOF motion base	Actual 205 dynamics

disturbances to the helicopter. The turbulence levels were created with a sum of nine sine waves differing in magnitude, frequency, and phase.

Position maintenance errors, subjective HQRs and motion sickness reports were collected for the hover task. Position errors were calculated based on the combination of lateral, longitudinal, and height deviations to derive a single value representative of the position error of the aircraft: position error = square root[(lateral error)^2 + (longitudinal error)^2 + (altitude error)^2].

Results

Examination of the HQRs of the hover maneuver (Fig. 7) supported the hypothesis that HQRs increased as visual time delay increases. The pilots reported that the increase in HQRs reflected a higher workload associated with the increased time delays.

In the no-turbulence conditions, HQRs increased with increases in visual delay, similar to the results obtained in experiment 1. At shorter visual delays (<134 ms), handling qualities were consistently rated as level 2. With longer time delays, the ratings increased from 1 to 3 HQRs, generally from level 2 to level 3. The data obtained in the moderate turbulence condition showed a general increase in HQRs over the no-turbulence case, and there was a similar trend of increasing HQR as delay increased. Whenever maximum turbulence levels were encountered, the HQR were steady in the level 3 realm (11 of 12 ratings). It appeared that the introduction of maximum turbulence washed out the effects of increased time delays.

For the control delays, similar effects were seen. Increases in time delay caused increases in HQRs, and increases in turbulence caused increases in HQRs from level 2 to level 3, reflecting increasing difficulty in retaining control of the helicopter.

With respect to position maintenance, pilots were consistently out of position, particularly in the longest delay conditions (Fig. 8). Average position error increased from 1 ft (with a ±1.2-ft rms error) to 4.9 ft (with a ±1.9-ft rms error) as visual delays increased (Fig. 2). In terms of control delays, the average position error increased from 1 ft (with a ±1.9-ft rms error) to 5.5 ft (with a ±4.3-ft rms error) as delays increased. The addition of turbulence caused similar but smaller increases in average position error (from 1 ft ±1.2 ft to 3.5 ft ±2.6 ft) in the baseline delay conditions. Turbulence, coupled with longer visual delays (≥134 ms) resulted in uniformly poor position maintenance, with the average error ranging from 3.3 ft (±2.5 ft) to 5.4 ft (±2.8 ft). In terms of control delays coupled with turbulence, the average position error ranged from 2.0 ft (±1.2 ft) to 7.1 ft (±4.0 ft).

Pilots 1 and 3 reported physiological symptoms of motion sickness, including eyestrain, vertigo, dizziness, and nausea, with increasing frequency and intensity as delay increased (Fig. 9). They consistently reported symptoms of slight-to-moderate strength at every exposure to the longest visual delay conditions (six reports from six exposures). They also frequently (three reports from six exposures) reported sickness symptoms in the second longest visual delay condition (184 ms). In contrast, only a single incident of a sickness symptom was reported from all of the control delay conditions, at the longest control delay, in conjunction with maximum turbulence. Note that there were nine exposures to each delay condition (three pilots with three levels of turbulence).

Discussion of Experiment 2

There was evidence to support all three of our hypothesis for this experiment. Both control and visual delays impaired performance, more motion sickness symptoms were reported in visual delay conditions, and turbulence affected handling qualities. The deterioration of system performance due to visual delays was evident in experiment 2 in both the HQRs and the objective (position error) data.

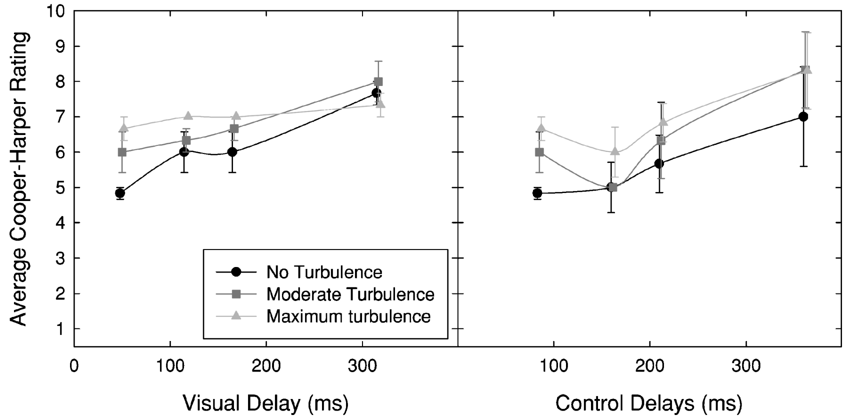

Fig. 7 Effects of turbulence and delay on simulator HQRs.

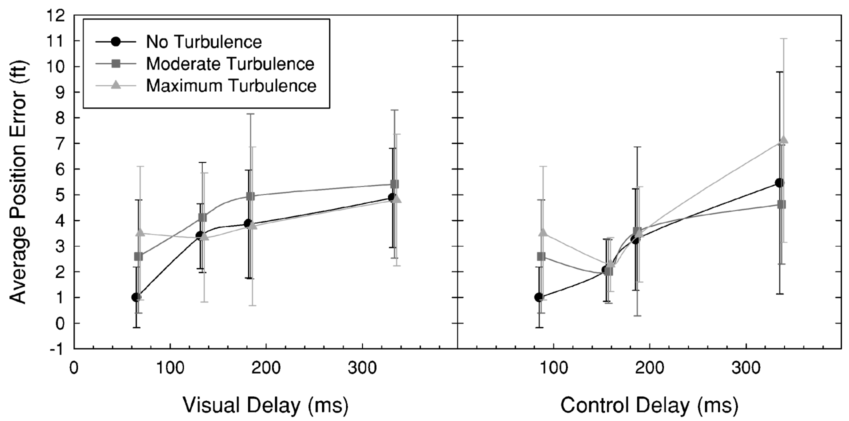

Fig. 8 Effects of turbulence and delay on simulator hover position error.

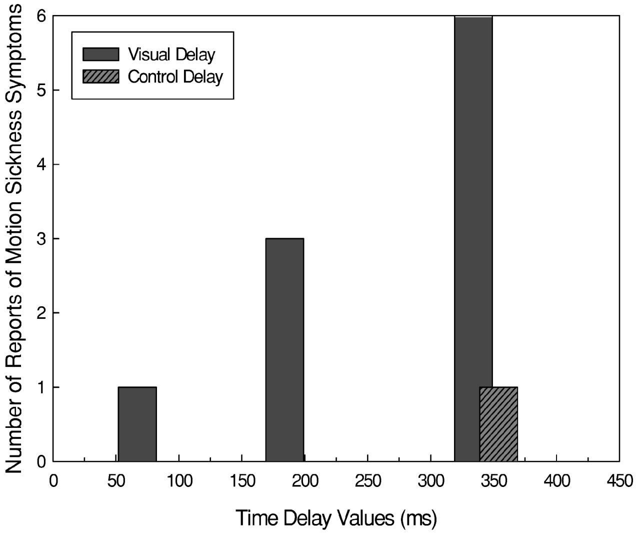

Fig. 9 Occurrence of sickness symptoms.

Even small amounts of visual delay resulted in deteriorating handling qualities and increased position errors. The HQR results were consistent with those from experiment 1, suggesting that the hover task was a practical means of assessing time delay effects. These data supported the pilots' comments from experiment 1 that the hover portion of the mirror C and the side step may have contributed to the difficulty of these tasks.

The introduction of turbulence to a system with visual/control delays increased HQRs. Although there were no reports of PIO, the HQRs in this experiment were indicative of the difficulties the pilots had in retaining control of the helicopter. These results were more in keeping with the effects of time delay noted in the literature.[13] The difference in difficulty in the current experiment as compared to experiment 1 was most likely due to the addition of turbulence, which increased the difficulty of the task.[5] According to the pilots, correcting for the turbulence disturbances increased workload because it required high-gain control inputs from the pilot. The high-gain inputs required to counter the turbulence worked in opposition to the reduced bandwidth control strategy adopted by the pilots to deal with the time delays. That is, the effectiveness of the reduced bandwidth strategy was negated by the insertion of turbulence, and it may be extrapolated that similar results (increased workload and decreased HQRs) would have been obtained in the flight trials if they had been flown in turbulent conditions.

General Discussion

The model outlined in Fig. 1 suggests that both visual and control delays would affect pilot/vehicle performance, and this result was observed in the current studies. The addition of delays in the control loop of a helicopter reduced handling qualities. As one would expect, the handling qualities effects did not appear to be dependent on the location of the delay. Although a performance decrement could be predicted from the model, one cannot easily predict from mathematical analysis the possible occurrence of physiological symptoms, nor their magnitude. In these studies we observed an increased incidence of motion sickness symptoms associated with the visual delay conditions in the simulator. We also observed postflight symptoms in the helicopter flight trials. It seems clear that new methods will need to be applied to assess the effects of long delays in the visual path.

In both of our experiments, the effects of time delay on performance measures and handling qualities were seen before motion sickness symptoms developed. This is consistent with previous results obtained in simulators.[38] As little as 134 ms of visual delay affected position maintenance, but relatively long delays ($\geq$184 ms) were required to consistently initiate sickness symptoms (experiment 2). We must emphasize again, however, that the effects of delay do not stand in isolation. There are interactions with the visual scene content, task dynamics, and individual susceptibility.

What are the implications of these results on the design and use of advanced visually coupled systems? We know excessive lags or delays in the visual feedback loop lead to degraded tracking performance, higher pilot workload, and worse handling qualities. Delays may also expose the pilots to conditions that induce fatigue, disorientation, and physical discomfort. There are a number of engineering approaches to solve this problem, but the critical element is determining, for each specific application, just what constitutes excessive delay. One can reduce time delays by using faster image processing equipment and higher bandwidth sensor platforms. The rapid advances in computer processing capability allow for some optimism in this area. Physiological symptoms may be reduced by adaptation/habituation training that minimizes the amplitude and frequency of pilot physiological symptoms. The effects of such training may not be consistent. In addition, some amount of re-adaptation is required each time an alteration to a person's visual input, for example, visual time delay, is encountered.[39] Pilots would be in a continuous series of adaptation, re-adaptation, and de-adaptation. Another approach to dealing with time delays is to use control system augmentation to reduce pilot workload. This approach has been successfully tested and evaluated for aircraft flight in degraded visual conditions, but it is not a panacea for visual time delays. Whereas control augmentation may reduce workload, it may increase control system latency due to greater processing requirements, reduce aircraft responsiveness, and it may further distance the pilot from the cockpit. Furthermore, it does nothing to eliminate or reduce the sensory conflicts that are thought to be involved in motion and simulator sickness.

Conclusions

Although visual delay may not be an important factor in current cockpits, future aircraft and space vehicles may use only synthetic or enhanced vision systems to provide the pilot with the visual information necessary for control. Given the increasing application of new visually based concepts and technologies to operational systems, the effects of visual delay should be thoroughly understood and included in the application specific requirements for any design.

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