AN INVESTIGATION OF HELMET-MOUNTED DISPLAY FIELD-OF-VIEW AND OVERLAP TRADEOFFS IN ROTORCRAFT HANDLING QUALITIES

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Abstract

Research engineers at NRC's Flight Research Laboratory studied the effects of binocular overlap and field-of-view on pilot workload and aircraft system handling qualities. They systematically varied both binocular overlap and the total field-of-view in two separate in-flight experiments. In each experiment, evaluation pilots performed a series of ADS-33 manoeuvres while wearing goggles that simulated a helmet-mounted display and, thus, limited their field-of-view. The effects of the goggles on pilot performance were evaluated using the following criteria: Cooper-Harper handling qualities ratings, visual cue ratings, pilot comments, and observer notes. It was found that handling qualities improved in a non-linear fashion as either the field-of view or the binocular overlap increased. Pilot comments, preferences and objective data agree with handling qualities data collected. The pilots adopted several strategies to overcome the limitations on the visual system introduced by the goggles. They increased their scanning head movements in frequency and magnitude, and they divided the visual fields into discrete zones for scanning. The results of the study show that reduced field-of-view and binocular overlap degrade helicopter system performance to the point where additional control system augmentation is needed to fly a helicopter safely in Nap-of-the-Earth (NOE) operations. The results suggest that full binocular overlap provides the best performance in practical situations.

Introduction

The increasing requirements for military helicopters and civil rescue helicopters to be flown in degraded visual environments (DVE) (i.e. bad weather, very low light level, or at night) during NOE operations, have driven the development of sophisticated vision-enhancing devices. One system under consideration for operation in DVE consists of a Helmet-Mounted Display (HMD) coupled to head-slaved vision sensors (i.e. Night Vision Goggles, Forward-Looking Infrared or Radar). NRC has developed a system, of this type, to investigate issues relevant to HMD design [Ref. 1]. Two important system characteristics that affect pilot performance when using an HMD are field-of-view *(FOV)* and *binocular overlap (BOL)*. Current generation HMDs significantly reduce the field-of-view compared to unrestricted human vision. In order to increase the FOV, designers partially overlap the displays, and the pilot sees a central binocular image flanked by two monocular images. This technique is particularly attractive to HMD designers because of the weight and size restrictions imposed on head-mounted devices.

Background

The HMD community, including manufacturers, users and researchers, has identified benefits and *problems associated with the use of partial* BOL HMD. A partial BOL provides a wide FOV, using current technology, with cost and weight savings. However, partial BOL has been associated with increased head movements, eye strain, fatigue and discomfort. These effects appeared to be more pronounced in displays with a narrow FOV (<30°) and small BOL (<20°). In laboratory studies, displays with small BOL have been shown to be susceptible to the phenomena of binocular rivalry and monocular suppression. It is difficult to determine how binocular rivalry and suppression affect performance when a complex visual scene is viewed. Some studies [Ref. 3, 4] have documented a fragmentation of the visual scene, where a user sees a bright central binocular region of the display, flanked by two dimmer monocular regions. There is some evidence that fragmentation of the visual field is seen more frequently when small BOLs are used [Ref. 5]. Others suggest that complex visual scenes may reduce rivalry effects [Ref. 6] and, therefore, these effects may not be as strong in practical situations where HMDs are used.

Recent studies have tackled FOV issues outside of the controlled laboratory environment. In several in-flight experiments, pilots performed practical tasks in a typical complex visual aviation environment. Bui, Vollmerhausen, and Tsou [Ref. 3] investigated the effects of a full overlap and 18° overlap HMD on pilot performance in helicopter flight testing. They found constricted eye movements, frequent head movements, higher workload and lower confidence with the partial overlap configuration in comparison to the full overlap configuration. Haworth et al [Ref. 7] and Edwards et al [Ref. 8] investigated the effects of varying the total FOV on pilot performance while maintaining a constant BOL. Their results showed the trend of improved handling qualities with increased FOV to a value which ranged from 60° to 80° FOV.

Purpose

There is little agreement among manufacturers and end users regarding the amount of partial binocular overlap and total field-of-view required for safe flight of an aircraft using HMD [Ref. 2]. The information available in the literature appears to be contradictory, and it is difficult to find data documenting the effects of a reduced binocular viewing region in a realistic task environment. It is necessary to investigate such issues and define desirable HMD system characteristics, in order to establish reliable design criteria for HMDs.

NRC's HMD research team investigated changes in pilot performance due to the trade-offs between the binocular overlap viewing region and the total field-of-view of an HMD. The first study looked primarily at the effect of field-of-view on aircraft handling qualities, and the second study looked at the effect of manipulating binocular overlap on aircraft handling qualities. This paper summarises the results of these two studies.

Study #1: Field-of-View Variation

Objective

The objective of this study was to determine how aircraft handling qualities were affected by changing the pilot's field-of-view. It was hoped that this would lead to the determination of a minimum acceptable FOV necessary for piloting an aircraft.

Method

Evaluation pilots flew a series of ADS-33 [Ref. 10] manoeuvres in NRC's Bell 205 airborne simulator, while wearing goggles with an interchangeable limiter mask insert that restricted the wearer's FOV. The goggles were modified welding goggles with a blackened interior, so that no extraneous light could penetrate the goggles. Peripheral vision was masked when wearing the goggles.

Table 1: FOV and BOL Configurations of the first Study

Configuration	Monocular FOV (°)	BOL (°)	Total FOV (°)
Baseline (no goggles or mask)	~160°H x 130°V	~130°	~200°H x 130°V
Goggles, no mask	75°H x 70°V, irregular	55°	95°Hx70°V
50° 100% BOL	50° dia. circular	50°	50° circular
50° 0% BOL	50° dia. circular	0°	100°H x 50°V irregular
40° 100% BOL	40° dia. circular	40°	40° circular
40° 0% BOL	40° dia. circular	0°	80°H x 40°V irregular
30° 100% BOL	30° dia. circular	30°	30° circular
30° 0% BOL	30° dia. circular	0°	60°H x 30°V irregular
20° 100 % BOL	20° dia. circular	20°	20° circular
20° 0% BOL	20° dia. circular	0°	40°H x 20°V irregular

Inside the goggles, a soft inter-ocular separator above the pilot's nose prevented either eye from seeing through the other eye's aperture. The size of the limiter mask apertures determined the total

FOV, and the spacing of the apertures determined the amount of overlap. The test configurations are summarised in Table 1.

Evaluation Manoeuvres

The following low altitude manoeuvres were adopted from the U.S. Army Aeronautical Design Standard (ADS-33D) [Ref. 10] for evaluation:

1. Hover,
2. Precision Landing,
3. Pirouette,
4. Acceleration-Deceleration (Quickstop), and
5. Sidestep.

These manoeuvres were selected because they represent a combination of two precision control input tasks (# 1, 2), a simultaneous multi-axis control task (# 3) and two dynamic large control input tasks (# 4, 5).

Evaluation Criteria

Evaluation Criteria used in this study were the Handling Qualities Rating (HQR) from the Cooper-Harper Scale [Ref. 11], evaluation pilot comments, safety pilot comments and a detailed debrief.

The Cooper-Harper Handling Qualities Scale: The handling qualities of the aircraft were evaluated using the Cooper-Harper Handling Qualities Rating (HQR) Scale [Ref. 11]. These qualities are affected by the vehicle dynamics, the disturbance environment, the task demands and the pilot's ability to perceive the environment, aircraft state and error state. Cooper-Harper HQRs are scored on a scale of 1 to 10. Low scores reflect better system handling qualities. Scores of 1 to 3 (i.e. Level 1 scores) indicate satisfactory handling qualities. Scores of 4 to 6 indicate performance that is satisfactory or adequate, but one or more system factors warrants improvement. Scores over 7 reflect unacceptable system handling qualities which require major system improvements.

Subjects: Three subjects performed the evaluations. They represented a wide range of helicopter piloting experience. Subject one was a research engineer who does not possess a helicopter pilot license but has been trained to solo standard. Subject one had little experience with NVG. Subject Two was an NRC operational pilot with fixed and rotary wing experience. He had 2400 flight hours in the helicopter and 25 NVG hours. Subject Three was a qualified test pilot with 2200 helicopter hours, and 10 flight hours using NVG.

All subjects were familiar with the Cooper-Harper HQR scale, and had used it previously.

Experimental Procedure

A pre-flight briefing was held with the pilots to inform them of the test procedure to be used. After the briefing, the goggles with limiter masks were calibrated for each evaluation pilot. The test aircraft in this study was NRC's Bell 205 airborne simulator equipped with a rate response control system. All flight tests were conducted with a crew of two persons, one evaluation pilot and one safety pilot. The evaluation pilot flew the manoeuvres from the right seat. Three pilots performed the flight manoeuvres on a field near the Flight Research Laboratory. The field was marked, with the course layout for the manoeuvres adopted from ADS-33D [Ref. 10]. The pilots performed the tasks under daylight visual meteorological conditions. Winds varied from near calm to 15 knots with occasional gusts. Prior to the evaluation, pilots had several practice trials for each manoeuvre. The trials were blocked by limiter mask type, which was presented in a random order. The manoeuvres within each block were always done in the same sequence: hover, landing, quickstop, pirouette, and sidestep. After the evaluation of each manoeuvre, the evaluation pilots documented their HQR, and their comments for a specific limiter mask. A debrief took place after each mask evaluation flight.

Results and Discussion

The Handling Qualities Ratings obtained in this FOV experiment (presented in Figure 1) are averaged across all pilots and all manoeuvres. The results reveal a clear trend, whereby handling qualities improved with increasing FOV, no matter which binocular overlap is used. The best HQR results were obtained with unrestricted vision, represented by the point at 200° FOV. A dramatic improvement from HQR 6 (Level 2) to HQR 3 (Level 1) is seen as the FOV increases from 20° to 40° in the 100% BOL case. The increase in Cooper-Harper HQR corresponds to an improvement in performance from barely meeting adequate performance criteria to easily meeting desired performance criteria.

The pilot workload during the test manoeuvres also decreased as the FOV increased. The workload decreased from "adequate performance requires extensive pilot compensation" (HQR 6) to "minimal compensation required for desired performance" (HQR 3).

No improvement was seen in the handling qualities above 100° FOV in the 100% BOL case.

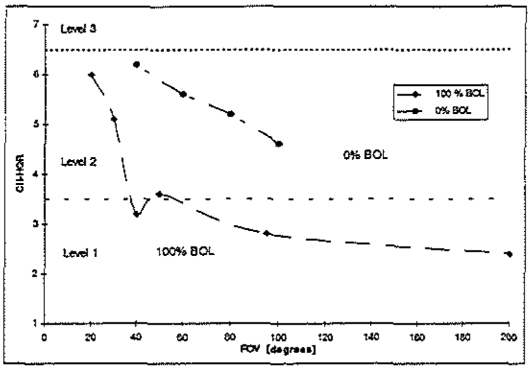

Figure 1: HQR Variation with increasing FOV

Level 2 handling qualities were obtained, whenever pilots wore a mask with 0% BOL. In the range of FOV tested, the 0% BOL was always rated at least 2 HQR worse than the 100% BOL. The 0% BOL affected pilot workload and system performance to the extent that desired performance was no longer obtained, and pilot workload was high. Furthermore, pilots reported that, with the 0% BOL, they were unable to judge height accurately.

There were manoeuvre dependent differences in performance, which are explored in more detail in the description of Study #2.

Conclusion

The results of this experiment show a non-linear correlation between handling qualities and FOV, in which pilot workload decreased with increased FOV and levelled off near 100° FOV with 100% BOL. Haworth et al [Ref. 7] found a similar result where performance levelled off between 60° and 80° FOV, depending on the test conditions.

Displays with no BOL are not recommended for use in flight, because of the severe degradation of handling qualities that they cause.

Study #2: Binocular Overlap Variation

Objective

The objective of the second study was to investigate a variety of binocular overlap configurations and their influence on pilot performance.

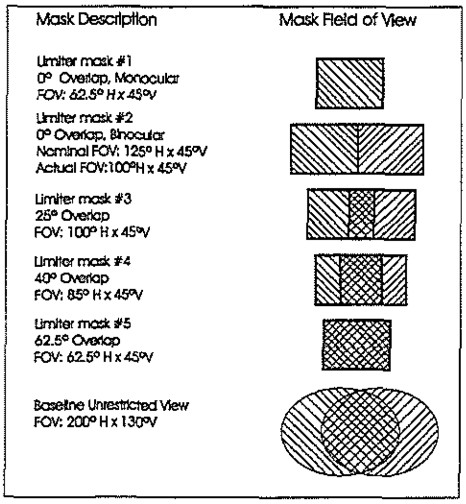

Figure 2: FOV and BOL Configurations

The range of binocular overlap and corresponding field-of-view configurations were selected according to results of NRC's first FOV study, other studies [Ref. 1, 2, 3, 5, 6, 9] and to simulate the monocular FOV (62.5°H x 45°V) and BOL settings of a CAE Fibre Optic Helmet-Mounted Display (FOHMD) used by the Flight Research Laboratory.

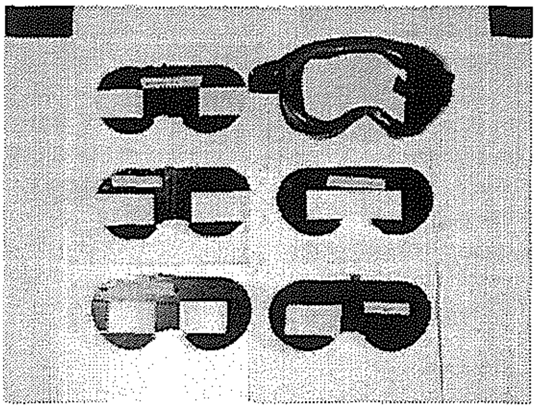

Figure 3: Modified Welding Goggles and Limiter Masks

Method

Restricting goggles similar to those in the first study, were used to vary both the FOV and BOL (as shown in Figure 2), while maintaining a constant monocular FOV of 62.5°H x 45°V. The actual FOV of the 0° BOL limiter mask (100°H x 45°V) differed from the desired nominal FOV due to horizontal limitations from the goggles. The modified goggles and limiter masks are shown in Figure 3.

The aircraft used in this study was NRC's Bell 206B, without special flight instrumentation, apart from a voice recorder

Evaluation Manoeuvres

The selected ADS-33 manoeuvres in this second experiment were the same as in the previous NRC FOV experiment. However the pitch angle performance criteria of the acceleration-deceleration manoeuvre and the bank angle performance criteria of the sidestep were reduced to maintain Level 1 handling qualities of the aircraft. These changes were made to compensate for the aircraft torque limits.

Evaluation Criteria

Evaluation criteria used in this study were the Handling Qualities Rating (HQR), the Visual Cue Ratings (VCR) from ADS-33D [Ref. 10], evaluation pilot comments, safety pilot comments, observer comments, and the results from a structured debrief. The accumulated information was used to assess the impact of the different BOL and FOV configurations on pilot performance and workload.

The Cooper-Harper Handling Qualities Scale: The handling qualities of the aircraft were evaluated using the Cooper-Harper Handling Qualities Rating (HQR) Scale [Ref. 11], discussed under Study #1.

Useable Cue Environment: Visual Cue Ratings (VCRs) were used to assess the cueing environment available to the pilot. The VCRs were determined for attitude, horizontal and vertical translational rate, using external visual cues and instrumentation. These ratings were then used to calculate the Useable Cue Environment (UCE). The UCE is a measure of the achievable level of aggressiveness and precision of helicopter manoeuvring. The UCE is a metric to quantify the control and stabilisation needed in a helicopter to compensate for degraded or missing visual cues.

Questionnaire: The results from a questionnaire, evaluation pilot comments, safety pilot comments and observer comments were used to access detailed subjective perceptions regarding the influence of the different mask configurations on achieved performance, pilot workload, and handling qualities.

Subjects: Four qualified test pilots performed the evaluations. Their relevant qualifications are outlined in Table 2.

Table 2: Subject Qualifications

Subject	Total Flight Hours	Helicopter Hours	NVG/HMD Experience
1	8800	2200	10
2	11200	2200	10
3	2600	2350	5
4	4100	3175	20

All subjects were familiar with the Cooper-Harper HQR scale, and had used it previously.

Experimental Procedure

The experimental procedure was the same as in Study #1, except for the following changes. All flight tests in NRC's Bell 206B were conducted with a crew of three persons: one evaluation pilot, one safety pilot and one observer. The evaluation pilot flew the manoeuvres from the right seat. The flight conditions were the same as the previous study.

After the evaluation of each manoeuvre, test pilots assigned an HQR, a VCR, and recorded comments for the specific limiter mask. The safety pilots added any appropriate comments. The observer documented observations regarding the evaluation pilot's scan pattern and head movements.

The order in which the limiter masks and the manoeuvres were evaluated was randomised to minimise learning and fatigue effects. Two baseline flights were used to assess learning effects. Following the first baseline flight, the pilots evaluated the five limiter mask configurations and then performed a second baseline flight. A detailed debrief took place after each baseline and mask evaluation flight. A final debrief for each pilot was held after the complete flight test.

Results

The results obtained during this investigation fall into three categories: Cooper-Harper Handling Qualities Ratings (HQR) for each binocular overlap, test crew comments and a Useable Cue Environment (UCE) Rating for each binocular overlap.

The Handling Qualities Ratings presented in the following figures are averaged results for all manoeuvres and test pilots. The two dotted lines, in Figure 4, represent the best and the worst HQR given for a specific overlap configuration.

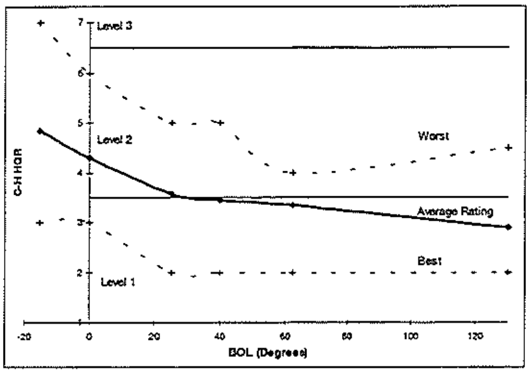

Figure 4: HQR Variation with increasing BOL

The results reveal a trend in HQR as binocular overlap increases. Handling qualities improve as the overlap is increased. The best HQR are clearly Level 1 and were obtained with unrestricted vision, represented by the point at 130° BOL. Pilots, on average, rated the monocular limiter mask (represented at -15° BOL) worst on the HQR scale. This was followed by the 0° BOL configuration. Both of these configurations were clearly Level 2. The averaged results for the 25°, 40° and 62.5°(100%) BOL limiter masks were very similar, and they straddle the Level 1 to Level 2 border.

The results of the flight tests also indicated manoeuvre-dependent differences in HQRs for a given BOL/FOV configuration as seen in Figure 5. That is to say, the workload increase due to limited BOL depends on the type of task being performed by the pilot. This agrees with both Bui et al [Ref. 3] and Haworth et al [Ref. 7] both of whom found that manoeuvre type interacted with FOV and BOL configurations. In this investigation, the hover task was the easiest task and was least affected by changing the FOV.

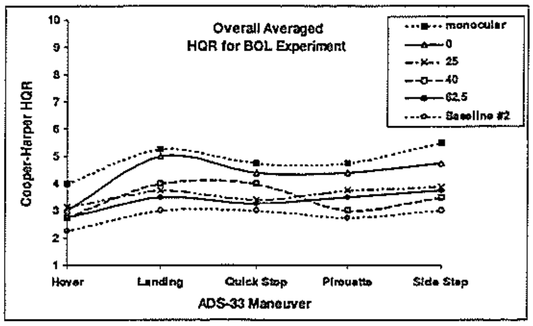

Figure 5: HQR Variations with Manoeuvres for all BOL Configurations

Useable Cue Environment: A Useable Cue Environment (UCE) was calculated based on Visual Cue Ratings (VCR) recorded by the evaluation pilots. The points in Figure 6 represent the average UCE for each specific binocular overlap. The Useable Cue Environment degraded substantially from the baseline condition, UCE 1, whenever limiter masks were worn. The monocular and the 0° BOL configuration are clearly UCE 2. According to Hoh, Baillie, and Morgan [Ref. 12], points on or near the border between UCE levels should be treated as the higher UCE level. Therefore, the ratings for the 25°, 40°, and 62.5° configurations located near the UCE 1 / UCE 2 borderline should be treated as UCE 2.

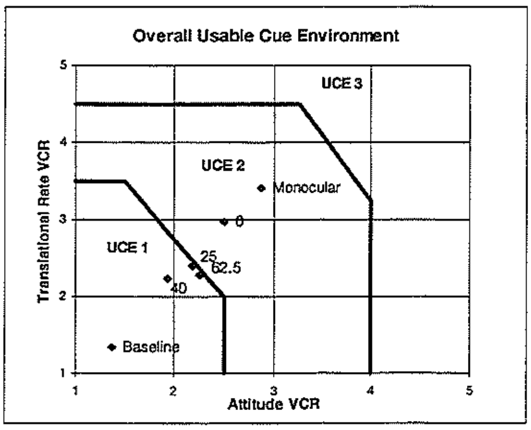

Figure 6: Useable Cue Environment (Average per mask)

Test Crew Comments: Pilot comments confirmed the results of the HQR and UCE tests. The comments have been arranged by manoeuvre.

Precision Hover: This manoeuvre was the easiest and consistently received the best HQR from pilots, as shown in Figure 5. Pilots commented that the hoverboard was an excellent cue to control the height and the lateral drift of the helicopter. All pilots preferred to look through the central binocular region of the masks to precisely detect drift from the desired hover position. Pilots used the array of cones placed on an angle to the hoverboard to determine their longitudinal movement and evaluate drift and drift rates. The test crew noticed that the pilot's ability to detect the longitudinal movement of the helicopter degraded substantially as BOL decreased.

Precision Landing: This was the most difficult task as shown by the worst HQR in Figure 5. During the vertical descent, pilots primarily looked through the helicopter's chin bubble to pick up the aircraft position with reference to the landing pad. Attitude cues were obtained by a quick glance through the front windscreen. As the helicopter descended close to the ground, pilots reported difficulty in maintaining a steady descent because they were unable to accurately judge their height above ground. This was especially noticeable in the last foot before touchdown. All pilots used the expression "I had to feel my way to the ground", and some pilots were surprised when they touched down while wearing the 0° BOL and monocular masks. It was evident to the observer and safety pilot that these masks greatly increased pilot workload, inhibited pilot performance, and reduced pilot confidence.

All of the masks inhibited the pilot's ability to distinguish between rolling and lateral movements, and between yaw and lateral movements.

Pirouette: During this manoeuvre, pilots looked out the front window to judge heading and out the side window to judge their longitudinal position and altitude. As the BOL decreased, they increased the frequency of their visual scan.

All pilots reported difficulty in the precise control of heading, and in the accurate judgement of height. Height control was most difficult while wearing either the 25°, 0°, or monocular masks. Two pilots commented that, when using the 0° BOL and monocular masks, they consciously used the familiar size of the indicator cones to evaluate their height.

The 40° BOL mask received the best HQR of any limiter mask for the pirouette.

Acceleration-Deceleration (Quickstop): As binocular overlap decreased, pilots pitched their head more frequently to see the course end markers, and the aircraft instrument panel. All pilots encountered difficulty judging height and longitudinal position when wearing any mask, but the 0° BOL and monocular mask caused exceptional difficulties. One pilot commented that, while wearing these masks his awareness of altitude was greatly impaired and he could not detect rapid descent rates. Consequently, the pilot felt he could not sense impending danger.

The test pilots had a great deal of difficulty performing the deceleration phase of the quickstop while wearing the 0° and monocular masks. In order to compensate for the lack of visual cues, the pilots memorised the timing of the control inputs, instead of relying on visual feedback. This led to an open-loop method of control, which could be dangerous in an operational situation.

Sidestep. With decreasing binocular overlap, the flight crew again observed an increase in workload, a degradation of situational awareness and a reduction in manoeuvre aggressiveness. This was especially noticeable when wearing the 0° and monocular masks, when pilots had problems perceiving heading, longitudinal drift, and height. One pilot noticed difficulty in creating a mental picture of helicopter attitude and motion due to the increased frequency of head movement, limited viewing area, and rapid helicopter movement when wearing the 25° mask.

Pilot Preferences: In the overall debrief, the pilots ranked the limiter masks from the most preferred to the least preferred. In general their ratings fell into three categories:

1. Unanimously, pilots most preferred the baseline no mask condition.
2. Pilots ranked three masks in an intermediate group: the 25°, 40°, and 62.5 ° BOL limiter masks. Pilots could not easily differentiate among these masks.
3. Pilots were unanimous in assessing the monocular and 0° BOL masks as least preferred.

Although pilots could not easily discriminate among the masks in the intermediate group, they made useful observations on these three masks.

Three of the four pilots preferred the 62.5° BOL mask (the 100% BOL mask). One pilot stated that he could make eye movements without sacrificing binocular vision, and he could easily focus both eyes on an object.

All pilots were aware of a lack of height control with the monocular mask and slowed vertical manoeuvring whenever they were near the ground.

Binocular rivalry effects were noticeable while using the 0° BOL mask. One pilot commented that his eyes "did not interact and share information."

General Comments

Pilots stated that they would need much higher situational awareness when operating a helicopter in an area with unknown obstacles than when flying around the familiar obstacle free ADS-33D course. They predicted a higher workload when flying NOE operations while wearing restricting goggles or an HMD.

Pilots were asked in the questionnaire about any unusual visual perceptions they observed while wearing the different BOL masks. They reported no significant unusual visual effects, such as luning or fragmentation of the visual scene, when using the 62.5°, 40°, and 25° masks.

The observer noted an increase in the magnitude and frequency of head yaw movements whenever a mask was worn. The observer also identified an increase in the frequency of head pitching movements.

Discussion of Study #2

The results of this binocular overlap in-flight study show that different combinations of BOL and FOV of Helmet-Mounted-Displays have a serious impact on performance, situational awareness and flight safety of rotorcraft operations near the ground.

Pilots found that wearing any limiter mask during flight affected their performance, reducing their effectiveness and manoeuvre aggressiveness. The masks affected the perception of height, produced a tunnelling of the visual field and a loss of peripheral vision, and created a "loss of general situational awareness." The mask limitations prevented quick and accurate capture of outside visual cues for attitude, translation, and position as well as quick and accurate readings of cockpit instruments. Pilots compensated for the reduced visual field with head movements that increased in frequency and amplitude. Pilots also divided the visual field into four major vision zones: front window, right side window, chin bubble and instrument panel. They also used additional minor vision zones.

In extreme cases, the pilots resorted to an open-loop control strategy to compensate for the lack of visual cues. This strategy was predominantly used when the head movement and zone scanning could not provide the pilot with the necessary cues to control the aircraft closed-loop, or when dynamic large control input tasks left the pilot insufficient time to scan for visual cues.

Conclusions of Study #2

In the baseline test configuration (unrestricted vision), test pilots determined the Useable Cue Environment as UCE 1 and the handling qualities as Level 1.

For the 25°, 40°, and 62.5° BOL conditions, pilots rated the UCE as borderline UCE 2 and they evaluated the handling qualities as borderline Level 2.

When pilots used the monocular and 0° masks, they ranked the UCE as UCE 2 and the HQR as Level 2.

Pilot comments strongly confirm the value of BOL in improving the safe performance of the quickstop, sidestep, and precision landing manoeuvres.

The test results confirm an improvement in pilot performance as the BOL increased. Pilot preferences and comments corroborated the handling qualities data and useable cue environment data.

There are several possible explanations for the similar HQR on the intermediate overlap conditions (25°, 40°, and 62.5° BOL). Either, the test criteria were not sufficient to discern the performance differences, or pilots were able to compensate for the changes in overlap without showing any workload related effects or the increase in the FOV compensated for the decrease in BOL.

As the discussion in the next section will show, the best explanation for the similar HQR is that the increase in FOV compensated for the decrease in BOL.

Overall Discussion

The results of Study #1 and Study #2 can be combined to give a complete picture of the relationship between FOV and BOL, as shown in Figure 7.

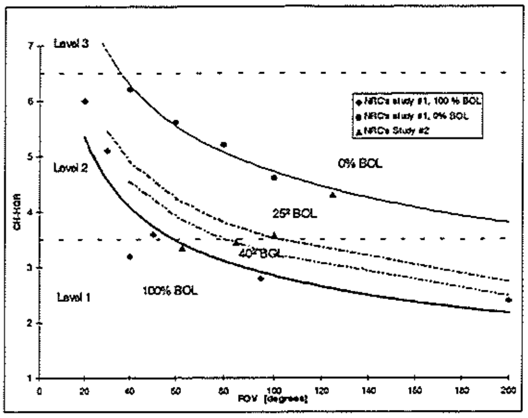

Figure 7: FOV and BOL Effects on Helicopter Handling Qualities.

The interpretation of the combined data must be approached with caution for the following reasons. Different aircraft were used in each study. The tasks performed in each study were similar but not the same. Each study used mask apertures of different shapes. Finally, the usual warnings apply to Cooper-Harper HQR data that have been averaged.

The lowest curve, shown in Figure 7, was generated from a power function regression on the 100% BOL data, yielding the equation $y = 17.185 \cdot x^{-0.3897}$, with an $R^2 = 0.8841$. A similar procedure was followed for the 0° BOL data. Curves of the same shape were then fit to the 25° and 40° BOL data by trial and error. The power curves accurately represent the behaviour of the data in the range of FOV and HQRs encountered during this study. The power curve does not accurately represent the data near the extreme end of the range at 0° FOV and HQR 10. However, the curves have been used to illustrate general trends and tendencies in the data.

Combined Results

The combined results of the two studies show that pilot performance is affected by both FOV and BOL. The effects of FOV and BOL are not independent.

Within the range of fields-of-view and binocular overlaps tested, and given a fixed monocular FOV for each eye, the best performance appears to be obtained when the two monocular FOVs are fully overlapped (100% BOL). This can be confirmed by looking at the data in Figure 7, where the 100% BOL line shows the best handling qualities.

Significant performance decrements are seen as the BOL is decreased from 25° BOL to 0° BOL.

Overall Conclusions

The study showed that binocular overlap is essential for manoeuvring near the ground, landing, and other NOE operations. It appears that the best performance is obtained with 100% BOL.

FOV limitations of displays degrade the UCE, which leads to poorer performance and increased HQR. The FOV effects were seen even in good visual conditions with a display of high resolution with no time delay. The results suggest that an FOV of 100° should be sufficient to provide Level 1 handling qualities. Improvements in handling qualities are marginal beyond 100° FOV.

The results of the study showed that the limited field-of-view and binocular overlap of Helmet-Mounted Displays degraded helicopter system performance to the point where additional control system augmentation is required to achieve Cooper-Harper Level 1 handling qualities. In UCE 1 conditions, a rate command control system is sufficient to give Level 1 handling qualities. This is the typical control response scheme for a helicopter. Most helicopters do not meet all of the rate response requirements to engender Level 1 handling qualities. When the visual environment is degraded to UCE 2 conditions, attitude augmentation is required to reduce the stabilisation effort required by the pilot. Based on the work of Hoh, Baillie, and Morgan [Ref. 12,13] as well as the recommendations of the ADS-33 [Ref. 10], an attitude command/attitude hold system in combination with a vertical rate/height hold system should provide Level 1 handling qualities even in a degraded UCE. A rate command control system alone will be unable to maintain Level 1 handling qualities.

There are two areas that clearly have not been answered in this study. First, these studies were undertaken with masks that simulated the FOV and BOL of an HMD. It may be the case that other characteristics of the HMD system, such as image resolution and time delay, affect pilot performance and interact with FOV and BOL limitations. Therefore, we suggest that a similar study should be undertaken with an actual HMD. Second, as mentioned earlier, these manoeuvres were done on an open course with known obstacles. It is suggested that further testing be conducted in a confined area with unknown obstacles and different visual cues.

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