How DVE Predisposes Rotary Wing Pilots to SD and Specific Countermeasures for Critical Phases of Flight

Dr. Robert Cheung

CANADA

bob.cheung@utoronto.ca

ABSTRACT

Spatial orientation requires the timely neural integration of concordant and redundant information from the visual, vestibular and somatosensory systems. Degraded visual environments (DVE) predispose pilots to SD (spatial disorientation) "traps". Specifically, DVE poses an insidious hazard during the critical phases of flight such as departure, approach and landings in the rotary wing. As brownout/snowball usually occurs close to the ground, there is little tolerance for error and correction delay. The sudden loss of external visual references would necessitate the transition from VMC (Visual Meteorological Conditions) to IMC (Instrument Meteorological Conditions) flying. The latency to re-acquire orientation (Cheung 2003, 2004) would increase in an unanticipated encounter with DVE. It has also been shown that oscillatory gravitational acceleration along the spinal (dorsoventral) axis of the body, which primarily stimulates the saccular macula of the vestibular system, leads to uncertain and usually erroneous perception of the direction of motion (Malcolm and Melvill Jones, 1974, Melvill Jones and Young, (1978). Similarly, sub-threshold lateral (along the horizontal plane) drifts cannot be detected by the vestibular system. In addition, blowing sand could induce a false sensation of self (aircraft) motion known as linearvection or circularvection depending on the direction of visual motion of the blowing sand and dust. Without reliable external visual references that provide essential information on the rate of closure and altitude, pilots may succumb to disorientation and subsequently make undesirable control inputs that could lead to fatality. Therefore, a requirement exists to address the inadequacy between flying tasks (approach, hover and departure in DVE), the lack of feedback for lateral, vertical drift, and height above terrain, especially in legacy aircraft with only standard flight instrumentation and limited flight control augmentation.

In 2011, the NATO (North Atlantic Treaty Organization) RTO (Research & Technical Organization) HFM (Human Factors and Medicine) Task Group 162 on Rotary-Wing Brownout Mitigation recommends that specific low speed symbology systems could provide an immediate near-term solution that will improve situation awareness (SA), prevent SD and reduce the occurrence of mishaps in DVE. (Albery et al. 2011). NATO Task Group 162 recommended two symbology systems concepts that have reached maturity for evaluation: A combination of conformal symbology system and egocentric display, and a flight display symbology that provides only egocentric and plan-view format with improved rate information and enhanced scaling for low speed flights.

In this chapter, we will present the results from a simulator and an in-flight study comparing the aforementioned symbology display systems. We hypothesize that intuitive HUD (Head Up Display) symbology sets (that require little or no cognitive processing) will be most effective to maintain or re-gain orientation during departure, hover and approach in DVE. Our results suggests that implementation of DVE symbology might yield an 80% reduction in risk during departure and approach in DVE conditions, and will have an extremely high impact on reducing the number one risk to rotary wing operations.

INTRODUCTION

For pilots, the ability to maintain spatial orientation in flight is essential for effective operation and survival. In order to maintain spatial orientation, one requires the correct perception of position, motion and attitude of the aircraft relative to a fixed frame of reference, which is the veridical vertical, and the Earth's horizontal surface. Spatial disorientation (SD) is the failure to perceive or perceive incorrectly the position, motion and attitude of the aircraft with respect to the aforementioned fixed frame of reference (Cheung, 2004). The modified operational definition for SD is an erroneous sense of the magnitude or direction of any of the aircraft control and flight performance parameters (Gillingham, 1992). There are a variety of disorientation scenarios and the circumstances that lead to disorientation also varied. The mechanism of spatial orientation is based on the neural integration of concordant and redundant information from the visual, vestibular and somatosensory (tactile cues and proprioception/joint angles information) systems (Cheung, 2004). Although the vestibular system provides an instantaneous registration of acceleration including orientation with respect to gravity, vision is often referred to as the predominant sensory input for spatial orientation because it is in our conscious prominence. Indeed, it is often said that 80% of the information that a pilot needed in flight is acquired visually (Stott 2013). However, there are many occasions when visual information may not be available or adequate such as flying in poor weather conditions (e.g. fog and mist), flying at night without night vision devices (NVG), NVG flight on zero illumination nights (<1.5 mLux) in "good" weather conditions and in conditions where there are blowing snow, sand, dust, ash or smoke. These degraded visual conditions are collectively referred to as degraded visual environment (DVE).

Specifically, "brownout" is a situation in which recirculation or blowing dust/desert sand from rotor downwash suddenly obscures both horizon and terrain features during departure and approach. Similar condition can be created by departure or approach in soft snow, conditions commonly known as "whiteout" but often referred to as "snowball" in Canada in order to distinguish from the phenomenon of "atmospheric whiteout". The start of brownout or whiteout typically begin with the aircraft enters ground effect. However, brownout is also dependent on numerous other factors such as the amount of sand and debris present, surface conditions, translational lift, rotor disk loading, rotor configuration, blade tip design etc. For example, the ground effect of the RCAF (Royal Canadian Air Force) Griffon CH146/Bell 412 is about 50 ft. above ground level (AGL).

The difficulty in maintaining orientation when encountering DVE has been known for a long time. Previous chapter has captured mishap statistics and the cost of brownout and whiteout accidents and incidents. There are physiological and perceptual limitations that could lead to SD during critical phases of flight (departure and approach) in the rotary wing. Physiologically, it has been shown that oscillatory gravitational acceleration along the spinal (dorsoventral) axis of the body, which primarily stimulates the saccular macula of the vestibular system, leads to uncertain and usually erroneous perception of the direction and velocity of motion (Malcolm and Melvill Jones, 1974, Melvill Jones and Young, (1978). Similarly, sub-threshold lateral drifts along the horizontal plane (direction and velocity of motion) cannot be detected accurately by the utricular macula. From the perspective of visual perception, in some circumstances, misleading cues could be more dangerous than the absence of cues. For example, blowing sand and snow could induce a false sensation of self/aircraft motion during hover known as linearvection or circularvection depending on the direction of the blowing sand and particulates. Linearvection is visually induced sensation of self-translation (aircraft-translation), and circularvection is visually induced sensation of self-rotation (aircraft-rotation) while the body/aircraft remains stationary. Without reliable external visual references that provide essential information on the rate of closure and altitude, pilots may succumb to disorientation and subsequently make undesirable control inputs that could lead to fatality.

As brownout/whiteout usually occurs close to the ground, there is little tolerance for error and correction delay. The sudden loss of external visual references would necessitate the transition from VMC (Visual Meteorological Conditions) to IMC (Instrument Meteorological Conditions) flying. After the transition, there is a latency to re-acquire orientation (Cheung 2003, Cheung et al. 2004). This latency would likely to increase in an unanticipated encounter with DVE. Therefore, a requirement exists to address the inadequacy between flying tasks (approach, hover and departure in DVE), the lack of feedback for lateral, vertical drift, and height above terrain, especially in legacy aircraft with only standard flight instrumentation and limited flight control augmentation. It is also critical that human factors issues such as situational awareness (SA), workload, performances and training implications of operating in DVE should be better understood.

POTENTIAL SOLUTION

In addition to pilot ground based and in-flight training in handling DVE conditions, technology development in response to the brownout/whiteout phenomena falls into four categories: 1. Improved handling qualities of the helicopter (i.e. with flight control augmentation, fly-by-wire system). 2. Specific symbology system concept for low speed flight during departure, hover and approach. 3. Sensor-based technology that could penetrate "see-through" or "see-remember" fine particulates. 4. The improved understanding and characterization of the dust cloud during brownout in order to provide physical, chemical abatement of particulates or flight procedure to reduce the risk of losing external visual references. Improved handling qualities could provide desired manoeuvrability and stabilization of the aircraft. However, ideal handling qualities is not enough to address all the DVE issues. Although the Technology Readiness Level (TRL) of sensor-based solutions varies and requires fusion but continues to improve; the associated system integration and human factor issues are more complex. The NATO Industrial Advisory Group (NIAG) concluded that no single sensor technology can provide the capability to 'see through' DVE and provide high resolution vision over the wide range of requirements for safe helicopter operations in various operational modes", some level of fusion is necessary (Van Donghen 2013). Other sensory cueing such as 3-dimensional audio and tactile cueing has been demonstrated in the laboratory, simulator and in the field. The ultimate challenge is the integration of all the four categories of technology developments as stated above. Sensor-based solution and the use of multi-sensory cueing and pilot training will be discussed in later chapters.

In 2011, the NATO (North Atlantic Treaty Organization) RTO (Research & Technical Organization) HFM (Human Factors and Medicine) Task Group (TG) 162 on Rotary-Wing Brownout Mitigation suggested that implementation of DVE symbology might yield an 80% reduction in risk during departure and approach in DVE conditions. Specifically, DVE symbology must address the physiological and perceptual limits as stated above: uncertain and erroneous perception of direction and velocity of vertical and lateral motion, and visually induced sensation of self-motion that could lead to SD. In addition, the latency to re-acquire correct orientation needs to be minimized. Two symbology systems concepts that have reached maturity for evaluation were recommended by TG 162: A combination of conformal symbology system concepts and egocentric display, and a flight display symbology that provides only egocentric and plan-view format with improved rate information and enhanced scaling for low speed flights (Albery et al. 2011).

Under the auspices of TTCP (The Technical Cooperation Program) AER (Aerospace Systems) TP-2 with participation from AS, CA, UK and US, a DVEST (Degraded Visual Environment Solution for TacHel) TDP (Technology Demonstration Program) was initiated to investigate the respective usefulness of these two symbology system concepts for the RCAF CH146 Griffon airframe. It is believed that symbology system concepts that works well in legacy aircraft with limited flight control augmentation will performed even better in modern day aircraft. Specifically, we investigated how the aforementioned two symbology system concepts could compensate for the lack of feedback for lateral drift, vertical drift, and height above terrain, in legacy aircraft with limited flight control augmentation. Summary of the methods, results and discussions of the simulator and in-flight investigations have been published in the Aerospace Medicine and Human Performance journal (Cheung et al 2015, 2015) and internal reports. Readers are welcome to contact the author for copies of the published scientific papers and detail internal reports. A description of the methods, results and conclusion of these investigations are provided below. It should be noted that since the DVEST investigations performed in 2013, there has been further development in DVE symbology system concepts and attempts in multi-sensory integration using audio, tactile and visual displays in flight control augmented aircraft. These will be covered in later chapters.

METHOD

The DVEST TDP program consists of two phases: the first phase is to conduct scientific evaluation of the symbology systems and related human performance issues in a simulator. The simulator investigation took place at the SIRE (Synthetic Immersive Research Environment) an H60 non motion-based flight simulator at the United States Air Force Research Laboratory (AFRL) at Wright Patterson Air Forces Base (WPAFB) in Dayton, Ohio. The flight simulator was re-configured to simulate the Griffon airframe. The second phase is an in-flight investigation of the two symbology systems on-board the NRC (National Research Council) ASRA (*Advanced Systems Research Aircraft),* C-FPGV, which is a modified Bell 412HP helicopter (similar to the RCAF CH146 Griffon). The ASRA was assessed and configured by two RCAF QTP (Qualified Test Pilots) so that the handling qualities of the fly-by-wire (FBW) attitude hold control model adequately represented the CH146 in terms of pilot technique and workload for basic flight manoeuvres that were investigated. The same group of RCAF operational Griffon pilots participated in both the simulator and in-flight investigations.

Investigation in the Simulator

Participants

A total of 14 active duty RCAF rotary wing male operational line pilots who received their respective commanders' approval were recruited as test subjects for this study. These pilots had accumulated between 550 to 4,900 hours of rotary wing flying time (mean 2231.5 ± 1332.8 hours) and were experienced with the Day HUD (Heads-up display). Two RCAF QTPs served as instructors for the test subjects and flight directors during data collection to ensure consistency between candidates with the procedures used to conduct the test manoeuvres. The QTPs also served as evaluator of the symbology system concepts from the perspective of research and development, and determined if they meet the prescribed standards. All pilots were considered to be on active duty and received no stress allowance or compensation for their time commitment. In addition to the 14 operational line pilots, we also collected data from five other QTPs from other countries and one pilot who had not flown for about 3 years. They had various experiences in different airframes and they had accumulated between 1650 to 4250 rotary wing flying time (mean 2626.7 ± 979.7 hours). All pilots completed an informed consent prior to participation. Only data from the operational pilots were used for analysis.

Experimental Design

We employed three interfaces in this study: (i) the current interface used on the Griffon, a 2 dimensional (2D) CH146 AVS7 (Elbit Systems Ltd.) served as the control. (ii) The conformal HDTS-DVE (Helmet Display & Tracking System for degraded visual environments) system with a 3 dimensional virtual reference and additional 2D symbols developed by Elbit Systems Ltd. (iii) The BrownOut Symbology System (BOSS) developed by AMRDEC, US Army with approach guidance towards a pre-planned landing point. All symbology displays were presented on the Elbit DDM described below. In other words, all three symbology systems used the same physical hardware and display. An additional head tracker was required for the HDTS symbology system.

A within subject repeated measures design was employed. Test subjects received familiarization training in the simulator and for each of the symbology system concepts prior to performing one practice and one data collection run of five manoeuvres, for each of the 3-symbology systems: AVS7 (A), HDTS-DVE (H), and BOSS (B).

- Manoeuvre 1: Single stage approach (landing);
- Manoeuvre 2: Single stage departure (takeoff);
- Manoeuvre 3: Two-stage approach;
- Manoeuvre 4: Hover turn;
- Manoeuvre 5: Two-stage departure,

Pilots performed the five manoeuvres in the above order for each symbology system but the order of the symbology systems presented was counter-balanced across subjects using a 2-Latin Square design (Table 1) where each symbology followed each other symbology an equal number of times.

Subject	Order 1	Order 2	Order 3	Order 4
1,7,13,19	A1-5	B1-5	H1-5	H6
2,8,15,20	B1-5	H1-5	A1-5	H6
3,9,16	H1-5	A1-5	B1-5	H6
4,10,17	A1-5	H1-5	B1-5	H6
5,11,18	B1-5	A1-5	H1-5	H6
6,12,14	H1-5	B1-5	A1-5	H6

Helmet Mounted Display

The helmet-mounted display (HMD) used to display all symbology systems was the Elbit Day Display Module (DDM). The display itself was identical in size and shape to the one currently fielded in the RCAF Griffon community, although with an updated connection system, see Figure 1 below. The helmet employed was the HGU-56/P with the DDM attached using a conventional night vision goggle mounting bracket. This HMD is considered a heads-up display (HUD) which minimizes the requirement to look at the flight instrument inside the cockpit, this allowing the pilot to concentrate his scan outside the aircraft. A HUD control switch for brightness control and mode selection was implemented on the helicopter collective grip.

Figure 1

Symbology system concepts

CH146 AVS7

The RCAF is currently using a CH146 specific version of the AVS7 by Elbit Systems Ltd. and we refer this particular symbology concept as AVS7 throughout this study. The AVS7 symbology used in the simulator study was created using a modified AMRDEC software version (vice production of CH146 hardware) and was equivalent to the CH146 AVS7 symbology currently in operation. The Master Mode Symbology of the CH146 AVS7 is depicted in Figure 2 below. It should be noted that the AVS7 was not designed to be used as primary-flight instrumentation and it was not designed for operations in degraded visual environment (DVE). There is no specific cueing set for approach, hover or departure in DVE.

Figure 2

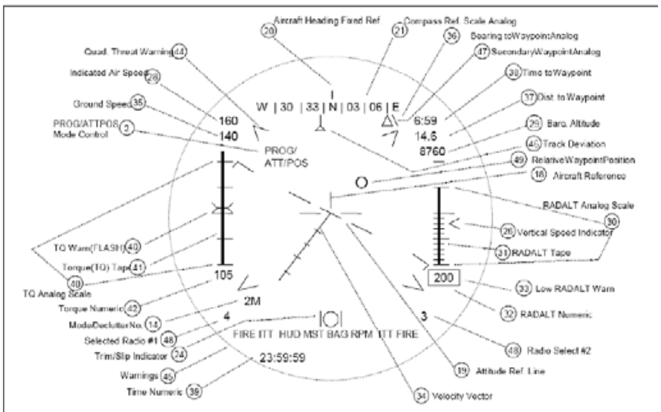
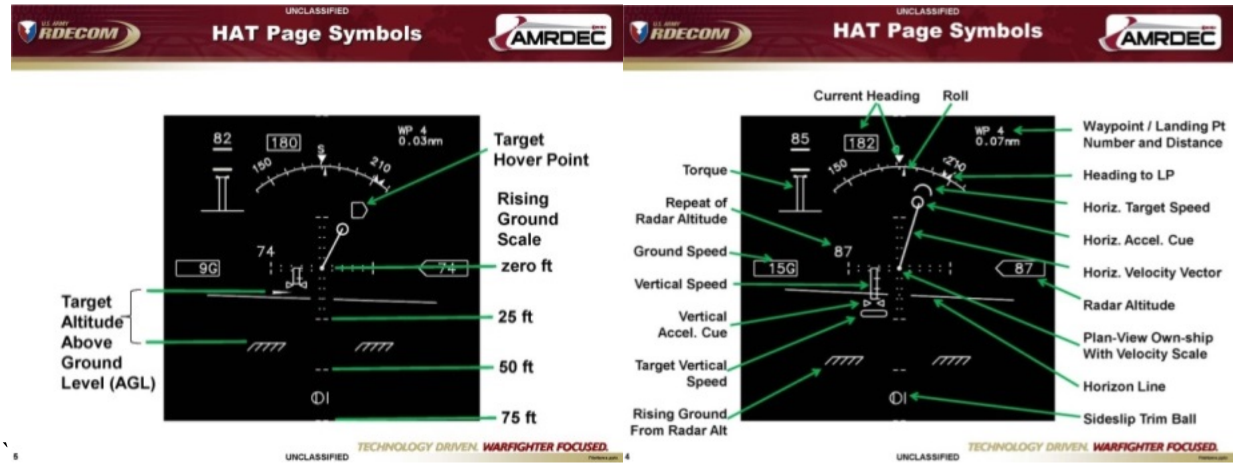


Figure 1. CH-146 Master Mode Symbology (LATEF2, Not to scale 28MAR00)

BOSS (BrownOut Symbology System)

The BOSS symbology set has been evaluated as a heads-down display for use in the H-60 Blackhawk helicopter with heading stabilizer capability to aid the pilot in performing approaches and landings in degraded visual condition (Szoboszlay et al. 2008, 2009, 2010; Harrington et al. 2010). The software version used in this study is designated as 13.04.04. There were the enroute (cruise) page and the Hover/Approach/Takeoff (HAT) page. Only the HAT page was used for this simulator investigation. The HAT page provides primarily a 2D display that included a flight director type of horizontal and vertical speed cueing to guide the pilot's collective and cyclic inputs during the approach phase to a pre-determined landing point. The HAT page (Figure 3 below) is composed of a combination of forward-view symbology and plan-view symbology. The forward view symbology is configured for an egocentric view point (depicted from the pilot's perspective) that included flight parameters such as torque, ground speed, heading, slip ball, radar altitude, target vertical speed, vertical speed, vertical acceleration, rising ground, own-ship reference grid and the horizon line. The plan-view format refers to a format in which the symbology is displayed from a vantage point directly above the aircraft. Plan-view symbology included target hover point, horizontal target speed, horizontal velocity, horizontal acceleration, heading tape and the own ship reference grid. The plan-view information was used to position the aircraft on the landing point (LP) at low speed when the aircraft was close to the ground. Two modes were available within the HAT page for the simulator trial: approach to landing (Figure 3 Right diagram) and approach to hover. The approach to hover mode behaved in the same manner as the approach to landing mode but the approach guidance terminated in a 50 ft. AGL (above ground level) hover instead of terminating on the ground. A target altitude AGL marker or "carrot" was added beside the vertical speed marker (see Figure 3 left diagram). In this study, the approach to landing mode was used for single stage approaches and departures, while the approach to hover mode was used for two-stage (or barrier) approaches and departures.

Figure 3



A reasonable analogy for relating the BOSS symbology to pilot control was that the horizontal acceleration cue "ball" symbol represented cyclic inputs (right hand control) and the vertical acceleration "bowtie" represented collective inputs (left hand control). The horizontal target speed "cup" symbol displayed the speed that the aircraft should be flown during the decelerating approach, and was designed such that the acceleration cue "ball" fits inside the target speed "cup". During approaches, the target speed "cup" moved towards the centre of the screen indicating the required deceleration profile and the pilot controlled the horizontal acceleration cue "ball" directly with the cyclic inputs and placed the "ball" into the "cup" in order to follow the correct deceleration profile. The target speed "box" represented the vertical speed that the aircraft should achieve in order to maintain a stabilized approach and was designed such that the end of the vertical speed tape should be placed inside the target "box". During approaches the target vertical speed box moved below the centre of the forward view own-ship reference to indicate an appropriate descent rate and the pilot controlled the vertical acceleration cue "bowtie" directly with the collective inputs and placed the "bowtie" in the vertical speed oval to achieve the correct descent profile on approach.

The target hover point (THP) was depicted as a home plate symbol, with its centre being the desired landing point with its shape oriented towards the designated approach direction. As the aircraft approached the LP, the THP moved towards the centre of the screen indicating the aircraft was nearing the LP. Once the aircraft was close to the THP, the pilot was able to transition from the horizontal target speed cue and placed the horizontal acceleration cue directly in the THP cue using the cyclic to achieve and maintain the desired position. As the aircraft approached the ground, or designated hover height, the rising ground cue or target altitude cue (in the approach to hover mode) moved into view from the bottom of the display based on the radar altitude. Once the aircraft was close to the ground or target altitude the pilot was able to transition from the target vertical speed cue and placed the vertical acceleration "bowtie" cue on the ground for landing or at target altitude to maintain the desired height. During approaches, hover and departures the pilots were required to maintain a heading scan as well and manually corrected to the desired heading throughout each manoeuvre. In order for the aircraft to land safely at the designated LP, the pilot had to manage four axes of control concurrently based on the symbology information: vertical axis (altitude), lateral axis (cross-track), longitudinal axis (speed) and yaw axis (heading).

HDTS-DVE (Helmet Display & Tracking System for Degraded Visual Environments)

The HDTS-DVE system combined 2D symbology with a 3D virtual landing grid that was precisely geolocated at a selected landing zone. Conformal symbology requires aircraft position, DTED (Digital Terrain Elevation Data) level II and EGI (embedded global positioning and inertial navigation systems). HDTS-DVE will also be referred to as HDTS from here on. The 2D symbology is shown in Figure 4 and included forward-view, plan-view and line-of-sight (LOS) symbology. Forward-view symbology included but was not limited to heading, torque, airspeed, groundspeed, barometric altitude, radar altitude, pitch ladder and the own-ship reference in the center of the field-of-view (FOV). Plan-view symbology included the same own-ship reference, horizontal velocity and acceleration, and the landing zone marker. The 2D LOS symbology represented real world (Earth-referenced) locations of certain objects from the pilot's viewpoint and included the boresight reticule unit (BRU), other pilot's LOS marker, flight path marker (sometimes called a velocity vector) and the landing zone position. The 3D conformal symbology system provided the pilots an augmented reality system shown in Figure 5 below, whereby symbols were drawn on the real world and viewed with the helmet mounted display. The 3D symbols were developed to assist the pilot during departure, approach, and hover in DVE and were optimized in previous development efforts to perform a no-hover landing task (Goff et al. 2010). The 3D symbology consisted of a circular landing zone marker and landing grid with towers and boxes whose size and perspective changed according to the position and motion of the pilot similar to what would be seen with real-world references. During the simulator trial shakedown flights the configuration of the 3D symbology was further refined to assist pilots with OGE (out of ground effect) hover by adding the two towers in front of the aircraft near the far edge of the grid and making the size of the boxes closer to the aircraft larger. 3D symbols also included virtual radar altitude arrows on the middle towers and approach and departure path marker arrows on the ground leading to and from the landing zone on the designated approach direction.

Figure 4:

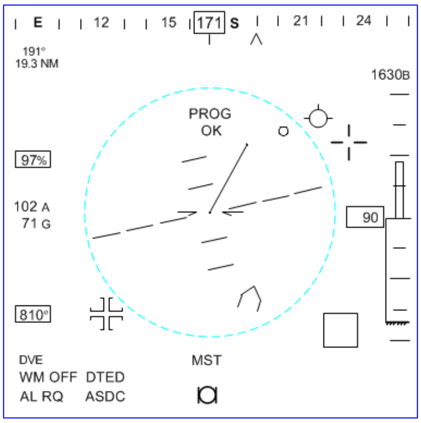


Figure 5:

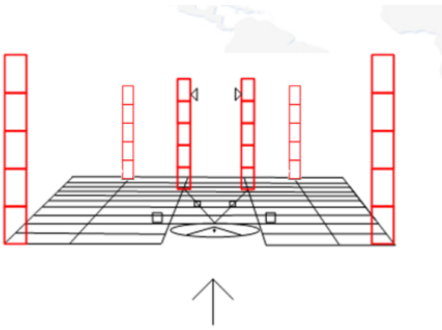
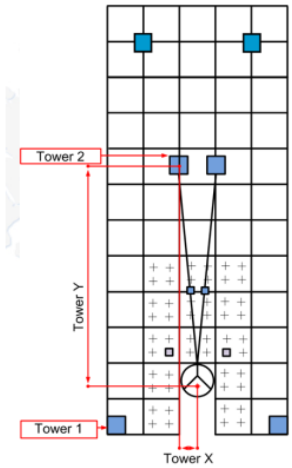
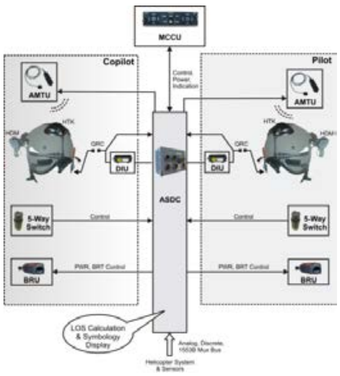


Figure 6 shows a close up of the horizontal grid where the grid texture (crosses) provides a higher resolution of drift information. (Illustration taken from: Degraded Visual Environments (DVE) Landing Using HDTS, Test Flight Pilots Briefing. Courtesy of Elbit Systems Ltd. April 2013)



A block diagram for the HDTS-DVE symbology system is shown in Figure 7, which outlines the major components of the symbology system. To provide useful conformal symbology the precise aircraft position and rate information was required in conjunction with the precise position and rate information for the pilot's helmet. In this study, an enhanced hybrid head tracker using a cockpit mapped electromagnetic field and integrated micro-electromechanical systems (MEMS) inertial sensor was used in order to minimize the latency generated with respect to pilot head movements. The head tracker system was mounted directly on the pilot's helmet, and an Advanced Magnetic Transmitter Unit (AMTU) was mounted inside the cockpit. The Advanced Sight and Display Computer (ASDC) received aircraft sensor information (such as embedded GPS/INS) and head tracker information and performed the required LOS calculations and symbol generation. To draw conformal symbology using aircraft position and altitude information the ASDC also needed Digital Terrain Elevation Database (DTED) information, which was provided as part of the simulator model. There were three main display screens made possible with selection using a 4-way switch installed on the collective or cockpit mounted Mini Converter Control Unit (MCCU). The NAV screen is a cruise flight basic HUD page, the DVE screen is the landing page for degraded visual environment conditions and the TKF screen is for departure and high hover consisting of the same DVE screen symbology with a slightly larger grid and towers. The simulator trial was conducted using only the DVE mode that is shown. The location of the LP was entered manually in the simulator or the pilot could centre the HUD LOS on a point on the ground and designate that point as the LP using the collective switch. It was also possible to re-designate the approach path direction and landing grid orientation at any time in flight.

Figure 7:



Procedures

The test subjects (operational pilots) were grouped into pairs and reported to the laboratory at a designated date within a period of two weeks for a two-day session of training and data collection. They were assigned to one of the QTPs who was responsible for their training in the simulator and who acted as flight director during their data collection. In the morning of Day 1, the subjects were given a pre-flight administrative briefing, and an overview of the DVEST program. A consent form, pre-simulator flight questionnaire about their experience, cumulative flight hours, and conditions of their health and vision were administered, followed by classroom instruction on the BOSS and HDTS symbology systems by the respective system experts. Two pilots were involved with each training and experimental session, the subject of the study was in the right seat and the flight director (one of the QTPs) was in the left seat.

In the afternoon of Day 1, each pilot was given a 30-minute session to become familiar with the operations of the simulator and the AVS7 symbology system. The familiarization was followed by two training sessions on the BOSS (45 minutes each) and two training sessions on HDTS (45 minutes each) using the assigned flight manoeuvres. In other words each participant was given a total of 210 minutes (or 5 sessions) of training on the symbology systems in the simulator. The order of training exposure to the BOSS and the HDTS was randomized across each pair of subjects. To avoid unnecessary fatigue and to facilitate learning, the two pilots and their respective instructors alternated their 45-minute training sessions in the simulator.

Data collection took place on the morning of Day 2 according to the randomized design indicated above in Table 1 and lasted for approximately 90 minutes. For each symbology system, the pilot flew each of the manoeuvres twice: the first complete run through of all manoeuvres served as a practise session. The instructor pilots provided a subjective evaluation as to the readiness of the subjects in mastering the three symbology sets as well as an overall readiness. Objective and subjective data were collected on the second run through session. Intra-trial questionnaires were administered after the completion of each manoeuvre with each symbology system. Data collection was followed by post-flight de-briefing in order to collect extended comments from each of the test subjects in addition to information solicited from a post-flight questionnaire.

Subjective Measurements

Pre-flight pilot questionnaires, were administered to the test subjects on their flying experience (cumulative career flight hours, aircraft types), quality of their vision and history of simulator sickness. Between trials, test subjects were asked to provide a subjective rating on a number of human factors issue related to their performance. They were provided with a copy of the subjective questionnaire and explanations for each of the rating criteria. This intra-trial pilot questionnaire (ITPQ) consists of the China Lake Situation Awareness (Adams 1998) scale, a modified Cooper Harper Workload Rating Scale (Cooper & Harper 1969) for mental effort and an evaluation of subjective perceived performance based on a 5-point Likert scale. In addition, a Perceptual Cue Rating (PCR) on attitude (including roll, pitch and yaw information), horizontal and vertical translational rate was included. A list of signs and symptoms related to simulator sickness were also administered. In addition, workload was evaluated using the NASA Task Load Index (NASA-TLX) which is a multidimensional subjective workload rating technique with six subscales: mental demand, physical demand, temporal demand, performance, efforts and frustration level (Hart 2006). Each of the subscale questions were rated on a scale of 0-20 where 0 = “very low” and 20 = “very high”. These questions were averaged into a single overall workload score. Immediately after the trials, a post-flight subjective report was administered followed by discussion on their relative performance with the instructor (QTP) and the principal investigator.

Objective Measurements

Objective test data included video recordings of the out-of-the cockpit scene with symbology overlaid, aircraft Time Space Position Information (TSPI), pilot's control position and the 2D horizontal deviation from the landing point. Flight parameter recorded during each flight in the simulator include airspeed, altitude, attitude, control column position, pedal position, trim positions and control surface positions and collective position. From this recording, the distance to landing point (LP), longitudinal (Lon) distance and speed, lateral (Lat) distance and speed, and vertical speed. Pitch, roll angle and heading error from initial position were calculated. Depending on the specific manoeuvre, different dependent variables for the objective assessment of performance were used.

Data Analysis

To avoid any potential bias, the subjective and objective data were analysed by two independent technical groups. The data were reviewed for consistency, plausibility, and out-of-range values. The subjective data was analyzed using repeated-measures analysis of variance (primarily) as well as regression and correlation approaches (Statistica (StatSoft Inc. Tulsa OK, USA)). Planned comparison was used to determine the significant differences among the three-symbology concepts. The level of alpha associated with each planned contrast is 0.05 to optimize the statistical power. Based on previous studies, the statistical power of this study is estimated to be approximately 0.8 at the α level of 0.05. For the objective data, the format of the analysis is the same for each manoeuvre. Raw data was plotted for each manoeuvre. Each dependent variable was used in a repeated measures analysis of variance, separately for each manoeuvre. Most dependent variables were skewed and logged (apply logarithmic value) to achieve normalization. The minimum, median, and maximum value for each dependent variable was determined. Subsequent repeated measures analysis of variance, used symbology as a factor. If the data was logged, the means for each symbology were transfomed back to the original units for tables and histograms.

Results

Summary of subjective responses: Initial analyses attempted to investigate if there is an effect of order for the 3 symbology system concepts. We found no evidence of an order effect. One operational line pilot was not able to participate at the last minute; therefore, we collected complete data sets from 13 operational pilots. The following tables present the percentage change for a given subjective measurement between AVS7 and the other two symbology system concepts (HDTS and BOSS). Negative (-) sign signifies percent improvement from AVS7 and positive (+) sign signifies percent degradation. Cells shaded yellow indicate a statistically significant difference ($p < 0.05$) in means. The statistical power is estimated to be 0.8 at the α level of 0.05. It should be noted that, in some cases the percentage change (improvement) from AVS7 is more than twice as high in HDTS as BOSS is.

Manoeuvre 1, Single stage Approach

	HDTS vs. AVS7	BOSS vs. AVS7
China Lake SA	-40.2%	-19.9%
Modified Cooper-Harper	-22.4%	-8.9%
Subjective performance	-26.5%	-13.5%

Attitude cueing	-37.3%	-17.3%
Horizontal translation rate cueing	-39.8%	-24.1%
Vertical translation rate cueing	-42.6%	-36.6%
NASATLX	-25%	-5%

Manoeuvre 2, Single stage Departure

	HDTS vs. AVS7	BOSS vs. AVS7
China Lake SA	-22.6%	+3.4%
Modified Cooper-Harper	-19.3%	+8.3%
Subjective performance	-17.8%	+4.4%
Attitude cueing	-33.1%	-2.9%
Horizontal translation rate cueing	-32.5%	-9.3%
Vertical translation rate cueing	-43.8%	-23.7%
NASATLX	-20.5%	-0.3%

Manoeuvre 3, Two-Stage Approach

	HDTS vs. AVS7	BOSS vs. AVS7
China Lake SA	-41.3%	-31.3%
Modified Cooper-Harper	-28.3%	-15.8%
Subjective performance	-26.8%	-23.3%
Attitude cueing	-46.4%	-27.9%
Horizontal translation rate cueing	-45.1%	-36.4%
Vertical translation rate cueing	-47.5%	-31.5%
NASATLX	-32.1%	-15.7%

Manoeuvre 4, Hover Turn

	HDTS vs. AVS7	BOSS vs. AVS7
China Lake SA	-31.1%	-31.1%
Modified Cooper-Harper	-27.2%	-25.3%
Subjective performance	-30.6%	-17.3%
Attitude cueing	-36.5%	-25.9%
Horizontal translation rate cueing	-36.3%	-24.2%
Vertical translation rate cueing	-28.3%	-18.9%
NASATLX	-29.2%	-16.7%

Manoeuvre 5, Two-Stage Departure

	HDTS vs. AVS7	BOSS vs. AVS7
China Lake SA	-44.0%	-30.0%

Modified Cooper-Harper	-35.5%	-26.6%
Subjective performance	-39.1%	-29.3%
Attitude cueing	-50.6%	-31.7%
Horizontal translation rate cueing	-42.8%	-34.6%
Vertical translation rate cueing	-54.1%	-38.6%
NASATLX	-40.9%	-22.9%

Summary of objective responses: Similar to the subjective assessment, initial analysis indicated that there was no evidence of a presentation order effect (F-test not statistically significant) therefore the only factor that was considered was the symbology system concepts (at 3 levels).

Results of Manoeuvre 1:

- Both HDTS and BOSS reduced the touch-down distance to designated landing point significantly during the single stage approach, although HDTS performed much better than BOSS, the difference did not reach significance.
- The absolute lateral distance to landing point is significantly shorter in HDTS than BOSS and AVS7.
- Both HDTS and BOSS reduced the longitudinal and lateral speed significantly although there was no difference between HDTS and BOSS.
- HDTS attained the best vertical speed and was significantly lower than both AVS7 and BOSS.
- HDTS was able to minimize heading error significantly compared to the other two systems and the root mean square error (RMSE) for the approach heading was significantly less than AVS7 and BOSS, while the RMSE for approach heading in BOSS was the highest.

Results of manoeuvre 2:

- HDTS maintains the lowest heading RMSE during the single stage departure.
- Although HDTS has the lowest heading RMSE, but it did not reach statistical significance when compared to BOSS.

Results of manoeuvre 3:

- Both HDTS and BOSS reduced the touchdown distance to pre-determined landing point (LP) and the absolute longitudinal and absolute lateral distance to LP significantly.
- The absolute lateral distance to LP was significantly shorter in HDTS than in BOSS.
- BOSS reduced the vertical, longitudinal and lateral speed significantly over AVS7, while HDTS reduced the lateral speed of AVS7 only.
- HDTS was able to minimize heading error significantly over the other two systems and the RMSE for the hover heading was significantly less than AVS7 and BOSS.
- Both BOSS and HDTS were able to significantly reduce the hover distance RMSE.

Results of manoeuvre 4:

- Both BOSS and HDTS were able to significantly reduce the distance to initial and lowest RMSE for the distance over AVS7 during hover turn, but there were no statistical differences between HDTS and BOSS.

Results of manoeuvre 5:

- Both HDTS and BOSS were able to minimize distance to initial position; heading RMSE, distance RMSE and altitude RMSE during two stage departure.

- HDTS provided the least heading error.

Discussion

In the simulator investigation, we selected single stage approach, single stage departure, two-stage approach, two-stage departure and hover turn as the test manoeuvres although it is unlikely that some of them (e.g. hover turn) would be performed in operational scenarios using real aircraft in DVE. The objective is to explore fully the capability of the respective symbology system concepts under stressful conditions when external visual references are not available. The main finding from this simulator study demonstrated that both the BOSS and HDTS systems are more superior to the current CH146 AVS7 symbology system in terms of the availability and quality of the orientation cues that are required under DVE. In addition, both systems are more superior in terms of workload and safety margins during DVE. In general, most pilots preferred the HDTS system and HDTS performed better than the BOSS symbology system. However, the differences in subjective and objective performance between BOSS and HDTS did not always reach statistical significance. In fact, both system concepts presented some strengths and weakness relative to one another.

It is not a surprising finding that the current CH146 AVS7 symbology system is inadequate for operations in DVE, as it does not possess a specific cueing set for approach or departure in that environment. From the post briefings, there were some consensus comments on the AVS7 system concept. While the AVS7 symbology system is not overly confusing, the scaling of the distance to the landing point is poor and the horizontal velocity cue is difficult to discern. It does not provide direct information on aircraft vertical rates or acceleration. The vertical rate had to be derived by the pilot based on changes in radar altitude. The horizontal translational rate cueing is poor as the horizontal cue becomes obscured in the own-ship symbol at low speed and there is no acceleration cue. There is also a significant scale jump between the 60-knot velocity vector and 10-knot drift vector. The pitch and roll attitude cueing provided only by movement of the own-ship reference relative to the horizon line are poor with inadequate scaling. In addition, the crucial information for flight control and navigation is not centralized; eye scanning/cross checking of instruments tends to be relatively slow and over a wide visual field making simultaneous altitude, heading and altitude control very difficult and increasing workload significantly. Although AVS7 provides an indication of the landing point (LP), it is difficult to comprehend the exact landing point and to detect small amounts of drift. It is relatively easy to lose situation awareness. Based on the post flight discussion and the results, under DVE orientation information provided by the CH146 AVS7 is inadequate and not user friendly. We do not recommend CH146 AVS7 for use during DVE operations.

There have been many versions of the BOSS symbology system since 2008. In this study, log 4 based horizontal velocity scale was employed. The roll tick-markers were deleted from below the heading (yaw) arc as there was some confusion regarding what direction the aircraft was actually yawing when the yaw indicator was moving during our preliminary (shakedown) investigation. It was suspected that this occurred due to heading marks on the outside of the heading arc moving opposite to aircraft yaw, while roll ticks inside the heading arc appeared to move in the direction of the yaw. In general, our results indicated that BOSS is more effective than AVS7 in executing the prescribed manoeuvres. The approach strategy was to control the horizontal acceleration cue “ball” symbol directly with cyclic inputs and to locate and track the acceleration cue “ball” symbol in the target speed “cup”. The vertical acceleration cue (the bow-tie symbol) is a predictor of vertical speed, and was controlled directly with the collective inputs by placing the symbol in the target vertical speed oval, and maintain its position. This approach guidance strategy was rated as the best feature among the three-symbology concepts especially in the two-stage approach. Our data suggested that approaches flown with BOSS appeared to be more controlled with fewer variations in the descent rate and horizontal deceleration. One could arrive near the landing area at a relatively consistent speed and altitude. However, the BOSS symbols were not necessarily intuitive, at least initially, and during hover and takeoff, landing, the symbology required significant mental processing effort; transitions to land using BOSS during DVE became much more challenging. There was some confusion with the BOSS symbology system as the information was presented with reference to the external world. For example, the horizontal velocity was indicated with respect to self (own-ship). However, the heading arc provided yaw information was based on how the world is moving. Under very high workload, it is easy for some pilots to display heading confusion possibly due to the confounding frames of references. As a heads-up display with narrower FOV, the position of the heading arc is too high in the visual field, pilots often lose track of the heading when paying attention to other elements lower in their FOV within the symbology page e.g. acceleration ball, rising ground etc.

The BOSS symbology system consists of some duplicate information that might have contributed to its being cluttered; for example, there were many indicators for vertical cues: RadAlt, rising ground, target altitude cue and RadAlt repeater (near the vertical speed cue). Although each indicator was useful for their own purpose, there was too much work required to interpret them all. During the two-stage departure when concentrating on the drift vector, at times pilots failed to recognise the 50 feet target altitude cue. The target altitude cue might not have been as obvious to some pilots while for some pilots, movement of the rising ground was undetected as it might not have been within their crosscheck. In addition, during the takeoff while the aircraft became light on the skids, pilots had to infer correct control inputs from horizontal velocity and acceleration cues, as the aircraft altitude information did not respond sufficiently until the aircraft began to lift off the ground and roll attitude fidelity was low. Interpretation of the precise aircraft attitude during liftoff was difficult and generally resulted in some drift during and immediately after takeoff with BOSS. In real-world operations, helicopter drift while light on skids would increase the risk of dynamic rollover if one skid were to become snagged on an obstacle near the landing point.

Our results indicated that in all manoeuvres, heading drifts were quite noticeable when using AVS7 and BOSS. The heading tape appeared to be out of pilots' crosscheck frequently when they were paying attention to other flight parameters such as the horizontal velocity vector and target hover point. Similarly, pilots had to re-direct their gaze to see the heading while paying attention to the acceleration ball, which created extra workload in maintaining heading. In order to execute a precise landing, one had to integrate information from all the symbols within BOSS. It required much higher concentration and mental processing time than the HDTS. In the BOSS system, if one parameter was far from desired it was difficult to correct the error as the normal workload left most pilots very little spare capacity and the crosscheck might not be fast enough to catch up. In addition, time spent to crosscheck repeatedly one parameter while correcting a significant error resulted in less time spent on other parameters with the net effect of causing other large errors to develop and even overall SA breaking down. With time, the frustration level increased, workload increased, pilots became overwhelmed with the task and fatigue set in.

Any low speed symbology systems including BOSS requires careful optimisation with the platform flight dynamics and control system, which in turn may require tailoring with the symbology system. Therefore, low speed symbology system is typically implemented on helicopters with flight control augmentation, for example, platforms with AFCS (Automatic Flight Control System) or "fly-by-wire" capability. As mentioned earlier, BOSS was developed as a head-down display (HDD) for the Blackhawk (H-60) helicopter which has heading hold capability and several studies demonstrated the effectiveness of BOSS in brownout landings in a Blackhawk in combination with dust penetrating sensors (Szoboszlay et al. 2010 Turpin et al. 2010). However, with conventional flight controls systems having limited augmentation, the BOSS symbology induces increased workload as demonstrated by our results. As mentioned previously, the pilot must concurrently manage four control axes: vertical axis (altitude), lateral axis (cross-track), longitudinal axis (speed) and yaw axis (heading). Extensive training may be required to achieve proficiency and develop specific control strategy in using BOSS. In this simulation study, pilots were specifically instructed to fly with the anti-torque pedals to simulate the Griffon flight dynamics and control system although the SIRE was equipped with the heading hold and its sensitivity was reduced. Post-flight comments from the participants indicated that the BOSS symbology system caused cognitive capture where attention was drawn away from the background as the instrument display and scanning requirement necessitated significant interpretation. In addition, there was coning of attention where the pilots become engrossed on a specific indicator to the detriment of others causing a loss of situation awareness.

The pairing of egocentric formatted symbology with imagery (generated on-board aircraft) in a forward-looking viewpoint allows for conformal (or scene-linked) symbology and creates the perception that the symbology is referenced the actual outside visual scene. McCann and Foyle (1995) reported that conformal symbology allows for concurrent processing between the imagery information and symbology information. With the exception of the Hover Turn manoeuvre, our data suggests that HDTS performed the best in all manoeuvres flown in the simulator. The percentage improvement from AVS7 was much higher when using HDTS than BOSS. The majority of the participants consider the HDTS system as intuitive, easy to understand, user friendly and most importantly, it reduced workload significantly. Having no previous information and limited training (210 minutes in total), most pilots were surprised that they could fly and land using the HDTS system with little difficulty in DVE.

Our objective measurements indicated statistically significant differences between the HDTS and BOSS in maintaining some of the most crucial flight parameters during approach in DVE. During the single stage approach, the HDTS system was able to maintain shortest absolute lateral distance to landing point, better vertical speed and the lowest RMSE of the approach heading. Similarly, in the two-stage approach, the HDTS system also performed significantly better in maintaining shortest absolute lateral distance to landing point, lowest heading error and lowest RMSE of the hover heading.

The HDTS symbology system provided good situational awareness when hovering over the landing zone due to the availability of crucial orientation cues of the aircraft during DVE. Specifically, the altitude reference (vertical towers and track bars) was visible at all time and made it easy to detect movement as it provided a natural way that enabled pilots to make correction with the (lateral) drift vector. It afforded fine-tuning of the landing although the rate of closure was difficult to judge in the version of HDTS that was used in the simulator. Similarly, there was less control information on fore-aft drift, especially when looking straight ahead. Nevertheless, some pilots almost regarded the moving grid reference as VFR flying, while the 2D symbology crosscheck is more consistent with instrument flying technique. In addition, HDTS only required the pilot to look at a point to designate a LP; therefore, the re-designation capability provided by HDTS would be advantageous during unanticipated DVE. Latency of the conformal symbology system is the delay between movement of the aircraft or pilot's head and the corresponding movement of the symbology to maintain its position on the ground. In a previous study, using an earlier version of HDTS, there were some concerns of head-tracker latency where the symbology was observed to "drag" in the direction of motion during pilot head movement (Purvis 2011). In this simulator investigation, there was not a single perceptible latency issue reported. Test pilots performed head frequency sweeps by tilting their heads up and down and turning from side to side with the HDTS; and results indicated that the head tracker lag only became significant at rates that made the pilots' normal visual perception difficult.

There were some perceived weaknesses with the HDTS. It was slightly more difficult to arrive at the designated landing area with precision, which may have been due to limited training on the system. It was most difficult to rely on the HDTS symbology to set a consistent glide path and deceleration so that one could arrive at the 3D grid at a predictable condition. Some pilots would typically come in very shallow and slow down early, dragging the approach in, so that they could take full advantage of the grid upon arrival at that point. One suggestion is to integrate the flight path marker into the symbology set such that one could use it early in the approach to establish the glide path. However, it would still be difficult to gauge the required deceleration if the out-the-window cues were not sufficient. It should be noted that we did not use the wingman capability from the HDTS, which help guiding the pilot into the area where the 3D landing grid appears. During the shakedown, as external visual cues were available in the simulation software before dust ball appears, such guidance might not be necessary and that it would lengthen the training and trial time. The 2D symbology of the HDTS could be useful during the final stage of the approach and during the hover but the scaling of distance to landing point and horizontal velocity and acceleration cues could be improved to better align on short final. It was also reported that changes of the horizontal velocity vector appeared to be distracting and the rate of movement of the home plate was difficult to resolve. Under cyclic step-inputs in the hover, the acceleration cue would deflect full scale until the velocity vector re-scaled. In addition, it was difficult to distinguish 2D and 3D symbology from one another when they overlapped and appeared to be cluttered, mainly in the DVE stage. To some pilots, the movement of the non-conformal 2D symbols relative to the 3D grid could induce a false sense of aircraft attitude change. The pitch scale in the HDTS was too small and difficult to visualize causing some pilots to rely on representations from external visuals (when it was available) to judge the pitch attitude. Lastly, it is possible that the use of conformal symbology could change the conventional instrument scanning strategy as the symbology is displayed virtually, ahead of the aircraft for landing. Another challenge with conformal symbology was that small pilot head movements if not perceived as such by the pilot could lead to false sense of motion due to the perception of conformal landing grid moving in response to the head tracker. Training and experience in using HDTS would minimize this effect.

In a real life situation, it is very unlikely that one would perform “hover turn” in DVE. During hover turn, one would normally minimize head movements during the hover. In this study, during the hover turn the tower symbols in the HDTS may not have been in their visual field, so there was a loss of references. In some cases, it was observed that pilots compensate by yawing their head to regain reference from the vertical tower symbol. Other pilots were able to use the horizontal grid of the heading tape readout as reference during the hover turn. It is anticipated that with further experience with the system, pilots would develop their own control strategy in executing hover turns.

In-flight investigation

Participants: Ten RCAF (Royal Canadian Air Force) rotary wing male operational pilots who had previously participated in the simulator investigation volunteered for the in-flight study. They had accumulated between 550 to 4,900 hours of flying time (mean 2231.5 ± 1332.8 hours) on the helicopter and experience in Day HUD (Heads-Up Display). In addition, 6 QTPs (Qualified Test Pilots) with various experience in different airframes and symbology system concepts also participated by conducting a broader evaluation of the BOSS and HDTS-DVE displays employing a number of advanced flight techniques. They had accumulated between 1650 to 4250 rotary wing flying hours (mean 2626.7 ± 979.7 hours). Only data from the operational pilots were used in the analysis.

Experimental design

The BrownOut Symbology System (BOSS) system and the conformal Helmet Display & Tracking System for degraded visual environments (HDTS-DVE) system were used for the in-flight investigation. A within-subject repeated measures design was chosen. In order to simulate degraded visual environment during the critical phases of flight (i.e. takeoff, hover and approach to landing), a custom light-proof blind flying hood (See figure below) was attached to the subject’s helmet. Pilots were instructed to pull the hood down at a specific time and continue to execute the designated manoeuvres using symbologies displayed by the Day Display Module (DDM, Elbit Systems Ltd) with a safety pilot in the right seat. When the hood was in the down position, it completely obscured the pilot’s external visual cues. The side window and the chin bubble of the left seat in the ASRA were also occluded during the flight trial.

A two stage departure followed by a single stage approach was employed during the in-flight investigation. They were performed in the same order for each of the symbology systems but the order of presentation of the symbology systems was counter-balanced across subjects where each symbology followed each other symbology an equal number of times.

Symbology system concepts

Based on the lessons learned from our simulator investigation, a number of changes to the respective symbology systems were proposed. Only changes that were made for the flight trial are described here.

Changes made in BOSS

The version of BOSS used for the flight trial was designated as 13.06.26. Similar to the investigation in the simulator, only the Hover/Approach/Takeoff (HAT) page was used and recommended changes that were implemented for the flight trial include the following.

- A heading error tape was added. It was set to appear when the aircraft was below 10 kt. And the heading error was greater than 3 degrees. Pilots were instructed to use the tail rotor pedals to “step on the tape” to correct the error.

- A heading “bug” was added on the heading tape to provide a reference to the pilots during the two-stage departure (Figure 4).

- The heading numeric box above the heading tape was re-located to the right of centre for the flight trial vs. the left of centre in the simulator investigation.

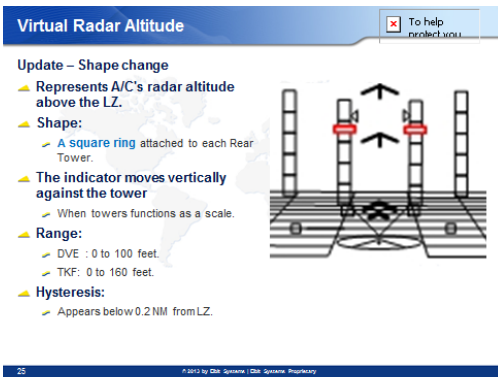
A screen-shot of the heading error tape which was user selectable when the heading error is more than 3 degrees (BOSS symbology version 13.06.26.) is illustrated below.

Changes made in HDTS-DVE

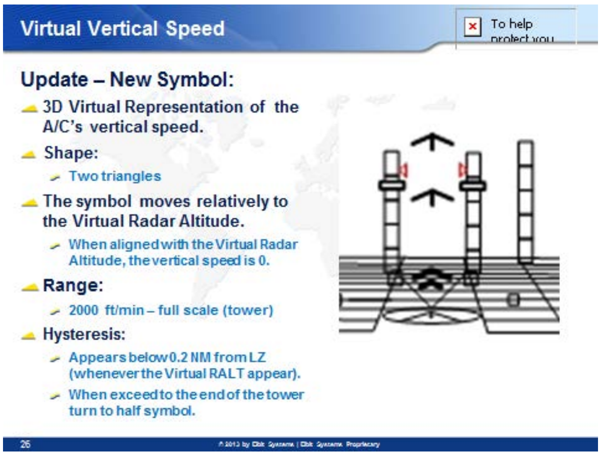
The HDTS 3D imagery was a false-perspective horizon- and ground-referenced grid drawing projected through the Day HUD. Vertical references were provided by towers and boxes arranged over the 3D grid. The intended landing point (LP) was indicated by a circle within the field with a Y-shaped symbol in the middle of the circle. Symbology control was handled by a 5-way thumb switch on the collective (See figure below).

The version of HDTS that was used for the flight trial is designated as August 2013. The 2D and 3D elements of the HDTS used for the flight trial were identical to those used in the simulator investigation with the following changes listed below.

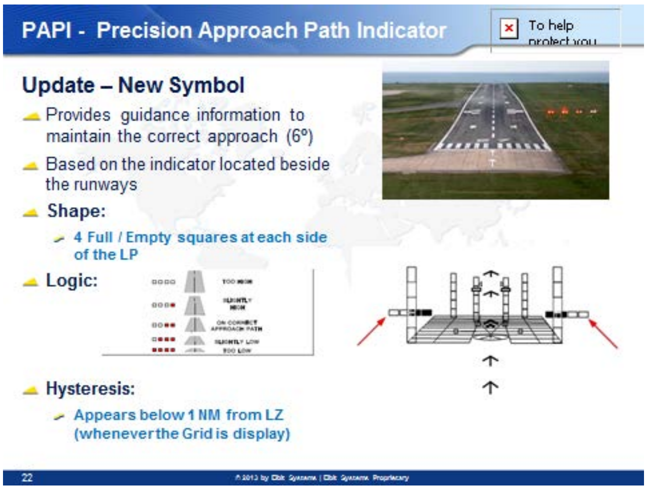
- The shape of the virtual RadAlt was changed from a triangular pointer to a square ring around the towers.



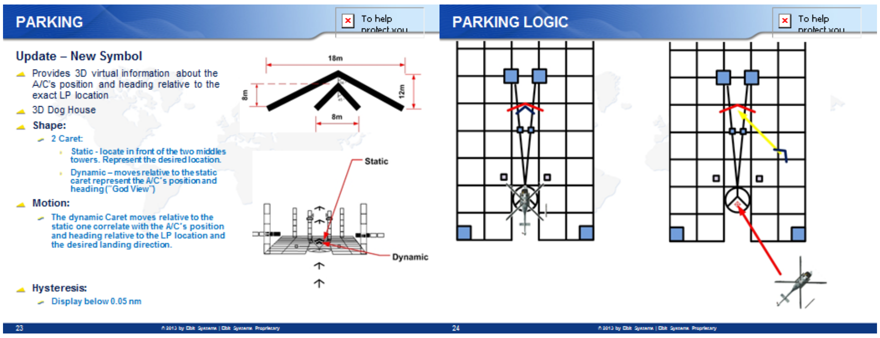
- Implementation of a new triangular symbol on towers to show virtual vertical speed with respect to virtual RadAlt.



- Implementation of Precision Approach Path Indicators (PAPI) to help maintaining the glide slope by having 4 horizontal rectangles. If the aircraft was on the correct glide slope, two of the 4 horizontal rectangles would be filled.



- Implementation of a new "Parking" symbol – it showed a "guiding caret", guiding the aircraft onto the designated landing point, it allowed for the determination of horizontal drift



- Implementation of some changes of the 2D elements are listed as follows:
  - Improved waypoint name.
  - Improved EGI status message, displayed “align” or “fail”.
  - Improved readability over 3D symbology adjustment of brightness and halo.
  - Velocity vector was set for one range with 2 different scales within the range (instead of have 2 different ranges switching back and forth which was found to be distracting and annoying during the simulator investigation).
  - Improved shape and scale of the pitch ladder to 25 deg.
  - Improved shape, scale and range of “dog house” landing zone (LZ) marker.

Procedures

Day 1 Classroom instruction and in-flight training

A pair of test subjects received a review and update briefing on the two symbology system concepts in the classroom followed by familiarization and training flights on the ASRA in the afternoon. The review and updates on the HDTS symbology system was given by a pilot from Elbit Systems Ltd. The subjects were also given a HDTS control checklist on how to align and operate the HDTS display in flight. An RCAF QTP reviewed the BOSS symbology systems and updates using previously recorded video on approach and departure that were taken during the “shakedown” flights. Specifically, the subjects were reminded of the crosschecks that were required during the low speed phase of flight (e.g. crosschecking the acceleration cue “ball”, altitude and heading) and for the approach (e.g. crosschecking the target speed “cup”, heading etc.)

Prior to the training flight, the subjects had an opportunity to practice on the controls of the HDTS and the alignment of the HUD. Both subject pilots were on board the aircraft for each training flight. During each training flight, the non-flying subject sat in the back cabin seating to view the symbology on a laptop computer. Each pilot received approximately 45 minutes of flight training for each of the symbology systems. The total duration of training for each subject lasted between 1.5 to 1.6 hours. For the HDTS symbology, the safety pilot initially landed 100 ft. back from the surveyed landing point so that the subject could align the conformal grid to the desired heading.

Day 2 Data collection flight

Prior to data collection, the sortie outline was briefed and the safety pilot and the subject were reminded that prompting and assistance will be minimized to safety concerns or gross error that must be corrected to meet the objectives of the study. Any significant deviations from the ideal, tolerances achieved, and anything unusual/remarkable about the flight sequence was recorded by the Flight Test Director (FTD). The FTD also ensured that the symbology video and the time when the subject was given control on each symbology sets were recorded. The data collection flight lasted approximately 1.2 hours for each subject.

Results

Subjective responses: Repeated measures analysis of variance (F: 1, 8 degrees of freedom) followed by paired comparison of symbology systems was performed.

Manoeuvre 1: Two-stage departure

- The HDTS system required significantly less mental effort and provided better situation awareness and subjective performance, although it did not reach statistical significance in all trials or for all questionnaire types.

- The overall workload based on NASA-TLX showed statistical significance between the 2 symbology system concepts, specifically, the HDTS system required significantly less effort, lower mental demand and higher perceived performance.

- HDTS afforded the best attitude cueing although it did not reach statistical significance in all trials.

Manoeuvre 2: Single stage approach

- HDTS required the least mental effort and provided better SA and perceived performance over BOSS in the single stage departure although it did not reach statistical significance in all trials.

- The overall workload for the HDTS was significantly lower than the BOSS system. Specifically lower mental demand, less effort and perceived higher performance.

- The HDTS symbology provided the best and statistically significant perceptual cueing in attitude, horizontal and vertical translational rate over BOSS.

Objective responses

The initial analysis indicated that there was no evidence of an order effect for the two symbology system concepts (F-test not statistically significant). In addition, there were no differences between the three trials within each symbology system. Therefore the only factor that was considered was the symbology systems (2 levels, HDTS vs. BOSS).

Two-stage departure:
In the two-stage departure, the root mean square (RMS) longitudinal error from initial departure and from initial hover when using the HDTS system was less than BOSS; however the difference was not statistically significant. Similarly, for the RMS distance error from initial departure position and from initial hover position, the RMS hover altitude errors and the RMS heading errors for the entire manoeuvre were smaller using the HDTS system than when using the BOSS system, but the differences were not statistically significant. The control activity as measured by the total time that force trim release was depressed during departure, hover and departure was shorter when using the BOSS system but not statistically significant. There was no significant difference in the DIMSS measurement of control activity during departure between the two systems. Specifically:

- The root mean square lateral error from initial takeoff: The difference between the HDTS and BOSS was marginal at $p < 0.06$
- The root mean square lateral distance error from initial hover position: The differenec between HDTS and BOSS was highly significant at $p < 0.018$ with HDTS achieved better performance (less error).
- The root mean square error of the altitude during hover: The difference between HDTS and BOSS

was significantly different at $p < 0.03$
- The track error during acceleration at Phase 3 of the departure: The difference in the performance between HDTS and BOSS was marginally significant $p < 0.055$
- Control activity during departure as calculated using the Dynamic Interface Modeling and Simulation System (DIMSS) metric: The difference between HDTS and BOSS was significantly different at $p < 0.027$. A larger number means a higher level of control activity (i.e. HDTS provided readily available orientation information hence increase control activity).
- Control activity during hover as calculated using the Dynamic Interface Modeling and Simulation System (DIMSS) metric: The difference between HDTS and BOSS was significantly different at $p < 0.025$.

Single stage approach:
For the single stage approach manoeuvre, the vertical, longitudinal and lateral speed attained at touchdown was lower when using HDTS but not statistically significant. There were no difference in pitch and roll attitude. The touchdown heading error, approach time from 50 ft. and approach time from 30 kt. to touch down were less in HDTS but not statistically significant. There were no differences in the force trim release during phase 1 and phase 2 of the single stage approach manoeuvre. The number of successful landings made was 23 out of a total of 27 landings or 85.1% (3 trials per symbology system for 9 subjects) when HDTS was used and 13 out of 27 landings or 46.1% when BOSS was used. Specifically:

- Average offset (lateral and longitudinal distance) from the desired landing position: There were significant differences between HDTS and BOSS in two dimensional distance to the landing point with the outliers ($p < 0.08$) and without the outliers ($p < 0.003$).
- Average offset (lateral, longitudinal and vertical distance) from the desired landing position: The difference between HDTS and BOSS in three dimensional offset from the landing point with outliers was not significant ($p < 0.08$) while without the outliers, the difference in offset from the landing positions was significant ($p < 0.003$)
- Average offset (lateral distance only) from the desired landing position: The difference between HDTS and BOSS in lateral distance from the landing point was statistically significant with outliers ($p < 0.001$) and without the outliers ($p < 0.001$)
- Average offset (longitudinal distance only) from the desired landing position: There was a significant difference between HDTS and BOSS in longitudinal distance from the landing point without the outliers ($p < 0.015$) but there was no difference when the outliers were included ($p < 0.13$) in the analysis.
- Average RMS heading error for single stage approach: The difference between HDTS and BOSS in root mean square heading error during the single stage approach was statistically significant ($p < 0.011$).
- Average heading standard deviation for single stage approach (symbology + clear hood view): There was statistical difference in heading standard deviation between HDTS and BOSS during Phase 1 ($p < 0.012$) and Phase 2 ($p < 0.001$)
- Control activity during approach phase 1 as calculated using the DIMSS metric: The difference in control activity between HDTS and BOSS was statistically significant for both Phase 1 ($p < 0.048$) and Phase 2 ($p < 0.001$) of the approach.

Discussion

The results of this in-flight investigation are consistent with our findings from the simulator study. For both the two-stage departure and single stage approach, the HDTS afforded better situation awareness, less mental effort, higher perceived performance, better perceptual cueing for roll, pitch and yaw attitude, horizontal and vertical translational rate. In addition, HDTS provided better NASA-TLX scores for all the six sub-elements (i.e. mental demand, physical demand, temporal demand, performance, effort and frustration). The objective measurements also reinforced that the 3D conformal symbology of HDTS provided better cueing and resulted in less error during departure and approach. During the two-stage departure, HDTS resulted in lower RMS lateral error from initial takeoff and initial hover, and lower RMS altitude error during and track error during departure from hover. Similarly, for the single stage approach, HDTS achieved significantly shorter lateral and longitudinal offset (distance) from the designated landing point and with less heading error.

From the DIMSS analysis, a higher score suggested a higher level of control activity. There was a higher DIMSS score for HDTS than for BOSS during takeoff and hover in the two-stage departure. Similarly, the DIMSS score was also higher during Phase 1 and Phase 2 of the approach. While there could be many possible interpretations, in consideration with other results, it is likely that with better overall cueing provided by the HDTS, subjects were able to spend more time controlling the aircraft based on the information that was available vice searching for information in the symbology. In other words, with less information readily available, fewer control inputs were possible. Although the DIMSS technique was designed to quantitatively measure the level of activity expended by the pilot, it should be noted that control activity may represent a specific level of workload to one pilot and another workload to a different pilot. In addition, control strategies utilized by the pilot depend on the aggressiveness of the pilot and the pilot's perception of task performance (Jennings et al. 2005).

In general, parameters that would directly affect the usability of any symbology systems in DVE include horizontal registration, vertical registration, symbology jitter, total display system latency, symbology head tracking and alignment (when applicable), helmet mounted display and symbology control. Both the HDTS and BOSS symbology systems possess their respective effectiveness and insufficiencies.

Effectiveness of the HDTS symbology system concept

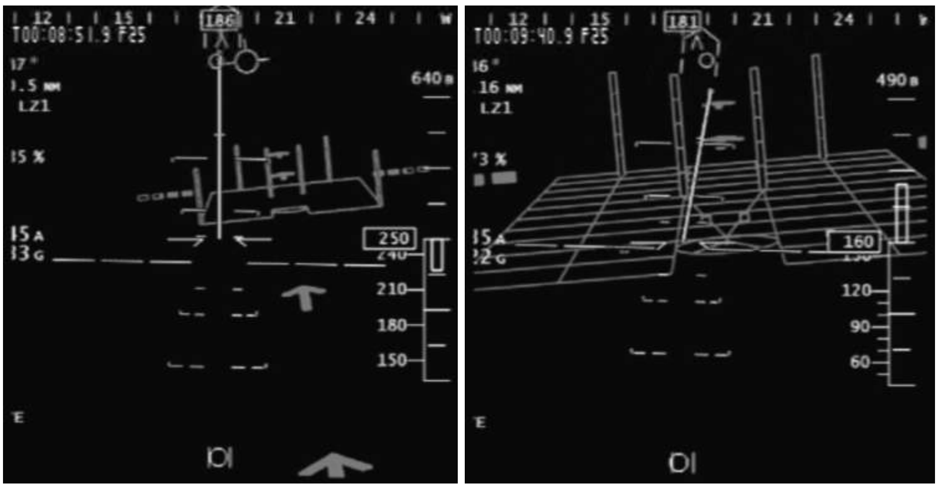
Based on the subjective and objective evidence from the flight trial, the HDTS symbology system was intuitive and provided overall better situation awareness and lower workload than the BOSS system during hover, landing and takeoff. Specifically, the conformal 3D grid in HDTS provided excellent lateral cueing during the 50 ft. hover and enabled the pilot to correct for any lateral and heading (yaw) drifts. For example, our results demonstrated that, for the majority of the subjects, task performance when flying with the blind flying hood down resulted in landings to a spot on the ground ± 15 ft. and holding hover height at 50 ft. ± 10 ft. without extreme effort. In addition, pilots were able to precisely control the vertical descent just prior to landing; during the final 0.2 - 0.3 NM inbound (once vertical velocity and altitude appeared on the vertical towers) because drift cues were quickly recognized with peripheral detection within their FOV while scanning for primary (torque, height, heading) information. However, the longitudinal drift cueing during hover is more challenging than lateral or yaw cues. Presumably because the longitudinal motion parallax cues in the limited forward FOV are more subtle than lateral or yaw cues. Indeed, pilots with a restricted field of view (e.g. night vision goggles0 would typically look off-axis to better perceive longitudinal drift. The towers on the HDTS were very useful for directional control and reasonable for vertical control. The changes made in the vertical speed indicator and RadAlt rings in the two middle front towers were helpful. The "tilted circle" at the centre of the intended LP indicating terrain slope based on calculation from digital terrain elevation database (DTED) information was intuitive. The rest of the reference symbology remained level with the horizon which was very useful at the point of touchdown, allowing the pilot to anticipate control inputs.

The arrows projected on the ground leading to the distant LP were clear and effective as they were correlated to terrain and allowed for easy recognition of a LP behind terrain. They induced a high level of confidence in most pilots when using the arrows as guidance towards the final landing. This symbol might be adaptable in future to serve as an en-route navigation cue for tactical flight (15-50 feet above ground for Griffons, 50-200 feet above ground for Chinooks). The static and dynamic carets/chevrons (parking symbols) provided excellent fore-aft motion cueing and guidance during hover and the final approach to landing. This was especially true when the aircraft was on top of the LP; no interpretation of the symbol was required. Similarly the conformal 3D provided useful longitudinal and vertical cueing during departure. One advantage of the HDTS system is that one can actually stop the approach, repositioned laterally and continued the approach. There were no perceived latency issue with the hybrid inertial-magnetic head tracker during head movements. Although it was not included in our test manoeuvre, by holding down a button the LZ symbology could be swept over the terrain, directed by the pilot's line of sight (LOS). The slope cueing circle was actively calculated and updated, which allowed a pilot to sweep the symbology over the visible terrain and effectively "searching" for a suitable landing location informed by DTED/slope calculations. It should be noted that the usefulness of a conformal display system is dependent on the accuracy and consistency of the registration against the real world. Symbols representing the ground must be congruent with the real world ground. This requires an optimal integration of specific, additional avionics including GPS/INS (global positioning system/inertial navigation system), head tracker (as indicated previously) and precision radar altimeter.

Perceived insufficiencies of the HDTS symbology system concept

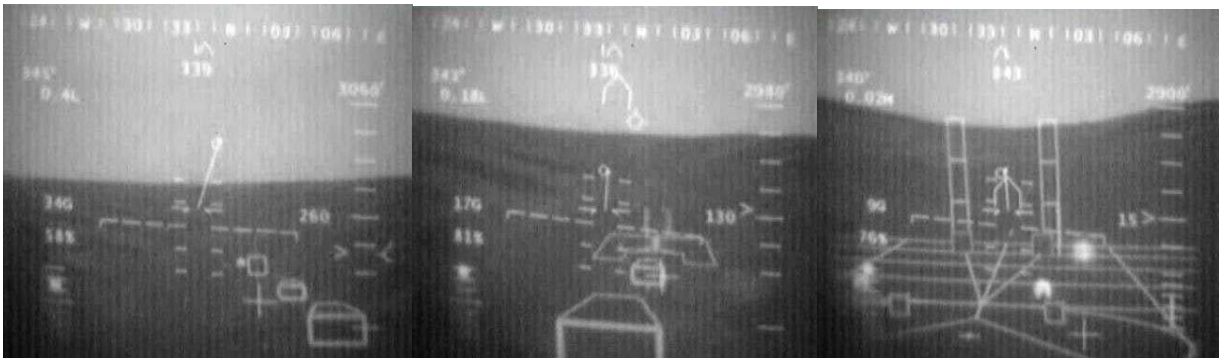
During the non-critical phase of flight in the single stage approach, it was difficult for the pilots to maintain the glide slope and rate of descent. The Precision Approach Path I (PAPI) is mainly used for approached to runways for which fixed wing aircraft fly constant speed approaches, vice a decelerating helicopter approach. There was no clear speed cueing with the HDTS on approach other than readout of the airspeed (or ground speed). Consequently it was difficult for pilots to maintain the correct PAPI indicators and conduct a decelerating approach by cross-checking speed. In one case, the subject maintained a glide slope that was "too high" and had to abort the approach due to the excessive airspeed. Some pilots would arrive too steep. Although the PAPI was helpful to some pilots, the indicators were positioned at the back of the grid on either side and out of the pilots' field of view (FOV). During crosscheck with the vertical velocity inside the 0.5 nm, pilots had to turn their head 30 degree off the approach heading. In addition, the PAPI did not show the rate of descent and were not easy to interpret. As a result, the PAPI might have disrupted the crosscheck and induced a higher workload in maintaining the proper rate of descent on approach. There were also some debates on the design of the PAPI, to some pilots, they appeared to be counter-intuitive. For example, while the PAPI was usually coloured coded, in a monochromatic situation, a "box that was not filled" would in fact appear to be darker and a "filled in box" appeared to be lighter. Additional approach guidance during the initial stages would be beneficial. The figure below (Figure 33) shows the clipped PAPI as the grid is approached during landings.

The Screen-shots of the PAPI during flight below demonstrated that full PAPI is visible on each side of the landing area (Figure on the left) at long range but clipped as the 3D grid is approached during landing (Figure on the right).



As discussed in the simulator investigation, the approach guidance "flying wingman" capability from the HDTS which provides deceleration cueing was not evaluated. The "flying wingman" symbol essentially guides the subject pilot (using techniques similar to formation flying) into the area where the 3D landing grid appears. In real flight, such guidance might not be necessary as external visual cues are available before the dust ball appears, unless the operation were taking place on a zero illumination night (<1.5 mLux). In the simulator study, as the pilot approached the landing zone, external visual references were in fact available. However, the use of the blind flying hood in the flight trials prevented the possibility of using external visual cues as guidance prior to entering the landing zone. If full capability of the HDTS system was used, during approach to landing, the 3D conformal symbology, wingman and line-up markers would have been included. The 3D grid would have re-scaled with time with the wingman guiding to the landing zone. At greater distance the 3D grid would have been represented by the 2D conformal marker (Figure 34A below) and as the ranges decreased, it would become a sparse grid (Figure 34B) and finally when closed in to the landing point, the full grid would have appeared. (Figure 34C) An investigation on an earlier version of the HDTS suggested that the wingman served as effective guidance (Goff et al. 2010) for deliberate approach (i.e. to a forward operating base).

Photographs of the HDTS system with the wingman symbology during approach. From left to right: A. at the start of the approach showing the 2D conformal marker and the sequence of the wingman boxes at the lower right of the photograph. B. A sparse 3D grid appeared as the aircraft was closer to the landing zone and the sequence of the wingman boxes at the lower centre of the photograph. C. A full 3D grid appeared at the landing zone (Courtesy of Elbit Systems Ltd).



Effectiveness of the BOSS symbology system concept

Our results suggested that during the single stage approach, the BOSS system was most effective from 300 ft. to 50 ft. The 2D symbology provided excellent glideslope and speed indication for the approach guidance to landing. As described in the simulator investigation (Cheung et al. 2014), during the decelerating approach, placing the horizontal acceleration "cue" ball inside the target speed "cup" to follow the correct deceleration profile worked well inflight as well. Similarly, by controlling the vertical acceleration cue "bowtie" directly with the collective inputs and by placing the "bowtie" in the vertical speed oval to achieve the correct descent profile worked equally well inflight. This type of cueing provided a target speed and descent rate to aim for and eliminated the need to interpret numerical values. In summary, BOSS provided a consistent approach and altitude guidance. To a certain extent, BOSS adapted to a profile depending on the initial conditions when reaching 0.8 NM. In tactical situation one could require more flexibility. This requirement of flexibility would also apply to the flying wingman symbols of the HDTS system. The implemented heading error indicator (arc) was found to be effective although it added to the cluttering of BOSS display. Similarly, when transitioning from short final to hover overlap of the cup/circle/dog house created clutter.

Perceived insufficiencies of BOSS symbology system concept

When the aircraft was below 50 ft. in the critical phase of flight (hover and landing), the task became more challenging and workload increased substantially leaving the pilot with little or no spare capacity. Specifically, the BOSS system presented horizontal, vertical and heading drift with separate cues, and in doing so, the pilot had to prioritize the crosscheck and interpret the cues at appropriate times. It was not easy to detect drift in one axis while correcting for drift in another axis and consequently once errors were allowed to develop they often compounded; the apparent lag in pilot input due to workload caused disorientation and frustration and at times a loss of faith in the system. In general if a pilot was focusing on position accuracy then altitude and heading errors would appear, and similarly when close to the ground and concentrating on altitude control, position and heading accuracy would suffer. Once errors built up (e.g. if the drift cue was greater than 5 kt.), they were difficult to correct and could lead to a loss of situation awareness due to rapidly changing values on all cues (“symbol soup”). There was also a tendency towards over-controlling, especially with the BOSS system, resulting in unnecessary large corrections. In general, BOSS required more interpretation and understanding; it also required a different control strategy than the HDTS or visual flying, more in line with an instrument cross-check.

There have been numerous reports on the effectiveness of the BOSS symbology systems in brownout landings (Szoboszlay et al. 2010, Turpin et al. 2010). However, our results from both the simulator and in-flight studies suggested that the BOSS symbology system induced increased workload as the pilot must concurrently manage the vertical (altitude), lateral (crosscheck) longitudinal (speed) and yaw (heading) axes. This is a classic example of workload versus flight control inner/outer mode. In our study with a conventional flight control system without a heading hold in the Griffon, the pilot was forced to account for and control the yaw axis, and the results of large heading errors and uncorrected drifts were not surprising. From the Aeronautical Design Standard (ADS-33) point of view, this is not a surprise finding. The decrease in pilot workload with attitude stabilization was quantified by a previous analysis on Attitude-Command-Attitude-Hold (ACAH) augmentation as a means to alleviate spatial disorientation due to DVE for low speed and hover in helicopters (Hoh 1998). One of the major findings during the development of the Aeronautical Design Standard Performance and Specification for Handling Qualities Requirements for Military Rotorcraft (ADS-33E-PRF) was that the ACAH control laws greatly reduced the workload for operations in DVE. On the other hand, the 3D conformal HDTS system presents cueing for all axes using conventional visual attributes (e.g. vertical towers) and allowed the maintenance of the heading within an acceptable standard.

Our findings that a 3D conformal system provided better situation awareness and workload during critical phases of flight are consistent with previous study by the US Army. In evaluating four representative display technologies (a head-up display, audio presentation, map display, and tactile display) in operationally realistic situations including takeoff and landing in both VMC and brownout degraded visual environment, the 3D conformal HUD demonstrated exceptionally strong effect on higher situation awareness, lower workload, better task performance, and higher preference (Davis et al. 2011). Furthermore, most recent data from the (Air SS) indicated that 3D symbology produced a 45% increase in aviator situation awareness, reduced pilot workload by 32% and reduced DVE related crashes during the landing phase by 90% (Guida & Issacs 2013).

CONCLUSION

Currently, there is little or no information or standardization as to what constitutes an optimal low speed symbology for DVE operations. However, for a symbology system to be effective in DVE, the information presented should be intuitive, requires little or no cognitive processing and possesses the properties of guiding attributes that are natural in maintaining orientation of the aircraft. Furthermore, it needs to compensate for the aforementioned vestibular and perceptual limitations. Our results further support motion, orientation and size as important guiding attributes. The conformal 3D landing grid with virtual towers, horizontal grid and designated landing zone overcome the vestibular inadequacies and provide the necessary orientation cues to land the aircraft safely without external visual references. Specifically, the vertical towers provide an intuitive cue of yaw and lateral drift and to a lesser extent, longitudinal drift. The seemingly more intuitive 3D virtual reference shortens the latency in re-acquisition of orientation cues (especially in lateral drift) when transitioning from VMC to IMC. The exact mechanism requires further laboratory investigation. An effective interface could negate the need for an expensive upgrade to heavily augmented digital flight control systems.

REFERENCES

Adams SR. (1998) Practical Considerations for Measuring Situational Awareness. Proceedings for The Third Annual Symposium and Exhibition on Situational Awareness in the Tactical Air Environment p. 157, June 2 & 3,1998. Piney Point, Maryland.

Albery W., Cheung B., Eger T. et al. (2011) Rotary-wing brownout mitigation: technologies and training. NATO RTO Technical Report, RTO-TR-HFM-162

Cheung, Bob, Kevin Hofer. (2003) Eye Tracking, Point of Gaze and Performance Degradation During Disorientation. Aviation Space Environmental Medicine, 74(1): 11-20.

Cheung, Bob, Kevin Hofer, Raquel Heskin, Andrew Smith. (2004) Physiological and Behavioural Responses to False Sensation of Pitch. Aviation Space and Environmental Medicine;75: 657-665.

Cheung, B. (2004) (Spatial Orientation – Nonvisual Spatial Orientation Mechanisms. *In*: F. Previc, W. Ercoline (Eds.) Spatial Disorientation in Aviation. Progress in Astronautics and Aeronautics Volume 203: 2004; 37-94. American Institute of Aeronautics and Astronautics, Inc. Restoin, Virginia

Cheung B0b, Andy McKinley, Brad Steels, Robert Sceviour, Vaughn Cosman, Sion Jennings, Peter Holst (2015) Simulator Study of Helmet Mounted Symbology System Concepts in Degraded Visual Environment. Aerospace Medicine and Human Performance 86 (7), July 2015 588-598.

Cheung Bob, Greg Craig, Brad Steels, Robert Sceviour, Vaughn Cosman, Sion Jennings, Peter Holst (2015) In-Flight Study of Helmet Mounted Symbology System Concepts in Degraded Visual Environment Aerospace Medicine and Human Performance 86 (8), August 2015 714-722.

Cooper, G.E., Harper. R.P. (1969) The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities. NASA TN D-5153. April 1969.

Davis, B. M., Jessee, M. S., Sapp, J. S. Morris, A. W. (2011) Human factors engineering evaluation (HFEE) of the air soldier system (Air SS) pre-milestone (MS) B decision early user demonstration (EUD). Internal report, Human Research & Engineering Directorate, Army Research Laboratory, April 2011.

Gillingham, K. K. (1992). The spatial disorientation problem in the United States Air Force. Journal of Vestibular Research, 2, 297-306.

Goff, C.P., Ball, A.N., Yapp, J.L., Pearce, S.J. and Crawford, F.L. (2010) Developing a 3D landing symbology solution for brownout Annual Forum Proceedings American Helicopter Society 66:422-434.

Guida, S. C. & Issacs, J. R. (2013) Product manager air warrior update to the field. Army Aviation Magazine October 31

Harrington, W., Braddom, S., Savage, J., Szoboszlay, A., Mckinly, R.A., Burns, H.N. (2010) 3D-LZ Brownout Landing Solution. Annual Forum Proceedings, presented at the American Helicopter Society

66th Annual Forum, Phoenix, AZ, USA. May 11-13.

Hart SG. (2006) NASA –Task Load Index (NASA-TLX) 20 years later. Proceedings of the human factors and ergonomics society annual meeting. October 2006 vol. 50, no. 9 904-908

Hoh, R. (1998). ACAH augmentation as a means to alleviate spatial disorientation for low speed and hover in helicopters. Presented at the American Helicopter Society International meeting on Advanced Rotocraft and Diaster Relief 21-23 April 1998, Gihu, Japan.

Jennings, S., Craig, G., Carignan, S., Ellis, K. & Thorndycraft, D. (2005). Evaluating control activity as a measure of workload in flight test. Proceedings of the Human Factors and Ergonomics Society 49th Annual Meeting 49: 64-67, Orlando, Fl.

McCann, R., Foyle, D. (1995) Scene-linked symbology to improve situation awareness. AGARD Conference Proceeding No. 555 Aerospace Medical Panel Conference on Situation Awareness 16:1-16:11.

Malcolm, R., & Melvill-Jones, G. (1974) Erroneous perception of vertical motion by humans seated in the upright position. Acta Otolaryngology 77, 274-283.

Melvill-Jones, G. & Young, L. R. (1978) Subjective detection of vertical acceleration: a velocity-dependent response. Acta Otolaryngology 85, 45-53.

Purvis, M. (2011) Testing 3D virtual world symbology for use in rotary wing brownout prevention. Symposium Proceedings Society of Experimental Test Pilots, 165-176.

Stott, R. (2013) Orientation and disorientation in aviation. Extreme Physiology and Medicine. 2:2, 1-11.

Szoboszlay, Z., Albery W., Turpin T., Neiswander G., (2008) Brownout Symbology Simulation (BOSS) on the NASA Ames Vertical Motion Simulator. Annual Forum Proceedings 1591, presented at the 64th American Helicopter Society Annual Forum. Montreal, Quebec, Canada. April 29 – 1 May.

Szoboszlay, Z., Turpin T., McKinley RA., (2009) Symbology for brownout landings: the first simulation for the 3D-LZ program. Annual Forum Proceedings, presented at the 65th American Helicopter Society International Annual Forum, Grapevine, Texas, USA. May 27-29.

Szoboszlay, Z., McKinley RA., Braddom SR., Harrington WW., Burns HN., Savage JC. (2010) Landing an H-60 helicopter in brownout conditions using 3D-LZ displays. Annual Forum Proceedings 1585, presented at the 66th American Helicopter Society 66th International Annual Forum 1585. Phoenix, Arizona USA May 11-13.

Turpin TS., Sykora B., Neiswander GW., Szoboszlay ZP. (2010) Brownout landing aid system technology (BLAST). Annual Forum Proceedings, 498, presented at the 66th American Helicopter Society International Annual Forum. Phoenix, Arizona USA May 11-13.

Van Donghen, N. (2013) Final Report of NIAG SG167 on Helicopter operations at low altitude degraded visual environment (DVE). NATO Industrial Advisory Group (NIAG), NATO Army Armaments Group (NAAG), Joint Capability Group Vertical Lift (JCGVL). NIAG-D(2013)0014, AC/225(VL)D(2013)0001.

ACKNOWLEDGEMENTS

The author would like to thank Dr. Andy McKinley, Dr. Greg Craig, Maj Brad Steels, Maj Robert Sceviour, LCol Vaughn Cosman, Mr. Sion Jennings, and LCol Peter Holst for their valuable contributions to this work.