Simulator Study of Helmet-Mounted Symbology System Concepts in Degraded Visual Environments

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BACKGROUND: A sudden loss of external visual cues during critical phases of flight results in spatial disorientation. This is due to undetected horizontal and vertical drift when there is little tolerance for error and correction delay as the helicopter is close to the ground. Three helmet-mounted symbology system concepts were investigated in the simulator as potential solutions for the legacy Griffon helicopters.

METHOD: Thirteen Royal Canadian Air Force (RCAF) Griffon pilots were exposed to the Helmet Display Tracking System for Degraded Visual Environments (HDTS), the BrownOut Symbology System (BOSS), and the current RCAF AVS7 symbology system. For each symbology system, the pilot performed a two-stage departure and a single-stage approach. The presentation order of the symbology systems was randomized. Objective performance metrics included aircraft speed, altitude, attitude, and distance from the landing point. Subjective measurements included situation awareness, mental effort, perceived performance, perceptual cue rating, and NASA Task Load Index. Repeated measures analysis of variance and subsequent planned comparison for all the objective and subjective measurements were performed between the AVS7, HDTS, and BOSS.

RESULTS: Our results demonstrated that HDTS and BOSS showed general improvement over AVS7 in two-stage departure. However, only HDTS performed significantly better in heading error than AVS7. During the single-stage approach, BOSS performed worse than AVS7 in heading root mean square error, and only HDTS performed significantly better in distance to landing point and approach heading than the others.

DISCUSSION: Both the HDTS and BOSS possess their own limitations; however, HDTS is the pilots' preferred flight display.

KEYWORDS: degraded visual environments, symbology system concepts, spatial disorientation.

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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.[4] 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. However, there are many occasions when visual information may not be available or adequate, such as flying in poor weather conditions, flying at night without night vision goggles, night vision goggle flight on low illumination nights ($<$ 1.5 mlx) in good weather conditions, and in conditions where there is blowing snow, sand, or dust. These degraded visual conditions are collectively referred to as degraded visual environments (DVE). Specifically, "brownout" is a situation in which recirculation or blowing dust/sand from rotor downwash suddenly obscures both horizon and terrain features during departure and approach. Similar conditions can be created by departure or approach in soft snow, conditions known as "whiteout," but often referred to as "snowball" in the Royal Canadian Air Force (RCAF) in order to distinguish from the phenomenon of

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atmospheric whiteout. Typically, the start of brownout or snowball occurs as the aircraft enters ground effect. For the RCAF Griffon (CH146) helicopter, ground effect begins at about 50 ft (15 m) above ground level (AGL). However, brownout or snowball 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.

The difficulty in maintaining orientation when encountering DVE has been known for a long time. In the RCAF between 1986 and 2006, there were 2 "snowball" related accidents and 54 incidents. The phenomenon of brownout has become a more prevalent operational issue because of the Iraq and Afghanistan missions. Brownout during departure was a direct causal factor of a RCAF Griffon crash in Afghanistan which resulted in three fatalities, three injured, and loss of the helicopter. Brownout and dust also contributed to a RCAF Chinook (CH147) roll-over in Afghanistan with four injured and a Griffon hard landing in Yuma during combat training. The Duncan Hunter National Defense Authorization Act[6] reported that during the U.S. Operation Enduring Freedom and Operation Iraqi Freedom, a total of 305 aircraft Class A mishaps (mishaps involving fatality, permanent total disability, $1 million or more damage) accounted for 81% of losses. Of the Class A mishaps, 75% were attributed to DVE (185 aircraft). As per the U.S. study, the European Aviation Safety Agency in 2011 has also identified that unexpected encounter with DVE is the number one risk to rotary wing assets.[7]

As brownout/snowball usually occurs close to the ground, there is little tolerance for error and correction delay. Therefore, a requirement exists to address the inadequacy between flying tasks (departure and approach 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. Current technology development in response to the brownout/snowball phenomena falls into four categories: 1) improving handling qualities of the helicopter (i.e., with flight control augmentation); 2) specific symbology system concepts for low-speed flight during departure, hover, and approach; 3) sensor-based technology that could penetrate (see through) fine particulates; and 4) improved understanding and characterization of the dust cloud during brownout in order to provide physical or chemical abatement of particulates, or flight procedures to reduce the risk of losing external visual references. In 2011, the North Atlantic Treaty Organization (Research & Technical Organization Human Factors and Medicine Task Group 162 on Rotary-Wing Brownout Mitigation) recommended that specific low-speed symbology systems could provide an immediate near-term solution that will reduce the occurrence of mishaps in DVE.[2]

There are two symbology systems concepts that have reached maturity (prototypes demonstrated in a relevant environment) for scientific 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 study, we employed the Helmet Display Tracking System for Degraded Visual Environment (HDTS, Elbit Systems Ltd., Haifa, Israel) for the former and the BrownOut Symbology System (BOSS, ARMDEC, U.S. Army, Washington, DC) for the latter concept. Both systems have been demonstrated separately in the simulator and in flight.[8,12–14] However, comparative scientific evaluations of the performance of these two symbology system concepts using the same group of pilots have not been conducted. In this study, using the same group of Griffon operational pilots, we attempted to demonstrate whether the HDTS and the BOSS symbology system concepts show significant improvements in aircrew performance during departure and approach in DVE using the current RCAF CH146 AN/AVS7 HUD symbology system as the control. The current manuscript describes the study conducted in the simulator. The in-flight study comparing the effectiveness of HDTS and BOSS in a Griffon helicopter will be presented as Part II of this study in a forthcoming issue.

METHODS

Subjects

Thirteen active duty RCAF male Griffon operational pilots were recruited as test subjects. These pilots had accumulated between 550 to 4900 h of rotary wing flying time (mean 2231.5 ± SEM 369.2) and were experienced with the Day heads-up display (HUD). All pilots maintained current medical certification in accordance with the Canadian Department of National Defence regulations and were considered to be on active duty. There was no stress allowance or compensation for their time commitment. Two RCAF Qualified Test Pilots (QTPs) who were familiar with the three symbology system concepts 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 maneuvers. The study was approved by the DRDC Human Ethics Committee (2012-037) and all subjects gave written informed consent.

Simulator Facility

Investigation in the simulator was conducted at the Synthetic Immersive Research Environment H-60 Black Hawk Flight Simulator, Air Force Research Laboratory, Wright-Patterson Air Force Base, Dayton, OH. The fixed base simulator included a 160-degree (horizontal) × 80-degree (vertical) visual field-of-view (FOV) provided by a 40-ft diameter hemispherical dome display used to present the out-the-window visuals. Audio simulation of the rotary wing environment was used during training and data collection. The visuals used the SubrScene simulation environment with detailed databases for landing zones located at Yuma Proving Grounds in Arizona. The visuals included a realistic brownout dust cloud generated by simulated downwash of the helicopter rotor blades. Participants sat in the right seat of a replicated H-60 helicopter cab developed by Protobox, Inc. (Dayton, OH). The cab contained six visual displays used to present simulated H-60 instruments and symbology display, but was not used in this study as we employed a helmet-mounted display. A control loading system designed by Wittenstein, Inc. (Chicago, IL), provided cyclic, collective, and pedal control inputs complete with adjustable force feedback, trim control, and trim release. The H-60 cab sat atop a hydraulically powered scissor lift that raises the cab to the proper eye height (approximately 5 ft or 1.52 m above the floor surface) for the out-the-window visual displays.

Although the Griffon (CH146) automatic flight control system does not have heading hold capability, the H-60 flight model with stabilization on simulated the CH146 attitude mode reasonably well and this was used for the trial. However, the H-60 model also provided a heading hold in yaw and this could not be turned off independently of the H-60 stabilization system. During the trials, the test subjects were not informed that there was a heading stabilizer and they were instructed to fly with the anti-torque pedals, and the pedal force gradients and damping were reduced as much as possible for the simulation study. The generation of the brownout dust cloud was based on distance to ground with brownout simulation beginning at 100 ft (30.5 m) AGL and total brownout was achieved when the aircraft was at 50 ft (15 m) AGL. The particle engine generated dust directly below the air vehicle. Forward velocity affects the formation of the dust cloud and the expansion rate of the dust affects the intensity of the brownout. Subjects were instructed to maintain the velocity of the aircraft below 15 kn as velocities above 15 kn will delay the effects of the brownout.

Equipment

The helmet-mounted display used to display all symbology systems was the Elbit Systems Day Display Module (DDM). The DDM was an electro-optical unit consisting of a liquid crystal display, lens, mirror, and combiner. The Elbit Display Interface Unit fed the symbology to the DDM. The display itself was identical in size and shape to the one currently fielded in the Griffon community, although with an updated connection system. The helmet employed was the HGU-56/P (Gentex Corporation, Carbondale, PA) with the DDM attached using a conventional night vision goggle mounting bracket (**Fig. 1**). This DDM is considered a HUD, which minimizes the requirement to look at the flight instrument inside the cockpit, thus allowing the pilot to concentrate his scan outside the aircraft.

Symbology System Concepts

The RCAF is currently using a CH146 specific version of the AN/AVS7 by Elbit Systems Ltd. and is referred to as AVS7 here (**Fig. 2**). There is no specific cueing set for approach, hover, or departure in DVE. There are four pages available to operators, a hover page, a transition page, a cruise page, and a blank page. For the simulator trials in the Synthetic Immersive Research Environment, we used the transition page that contains elements common to hover and transition.

BOSS

The BOSS symbology system concept provides scaled indication of acceleration, drift, ground speed, rate of descent, and rate of closure toward a preplanned landing point. The BOSS symbology set was developed based on different variants of new helicopter primary flight display symbology that were evaluated in the NASA Ames Vertical Motion Simulator. It has been primarily 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 DVE.[9,13–15] The software version used in this study is designated as 13.04.04; for this study we used the Hover/Approach/Takeoff (HAT) page (**Fig. 3**). The HAT page provides primarily a 2D (two dimensional) display composed of a combination of forward-view symbology and plan-view symbology 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 predetermined landing point. The

Fig. 1. The Day Display Module mounted on the HGU-56/P helmet using the night vision goggle mount.

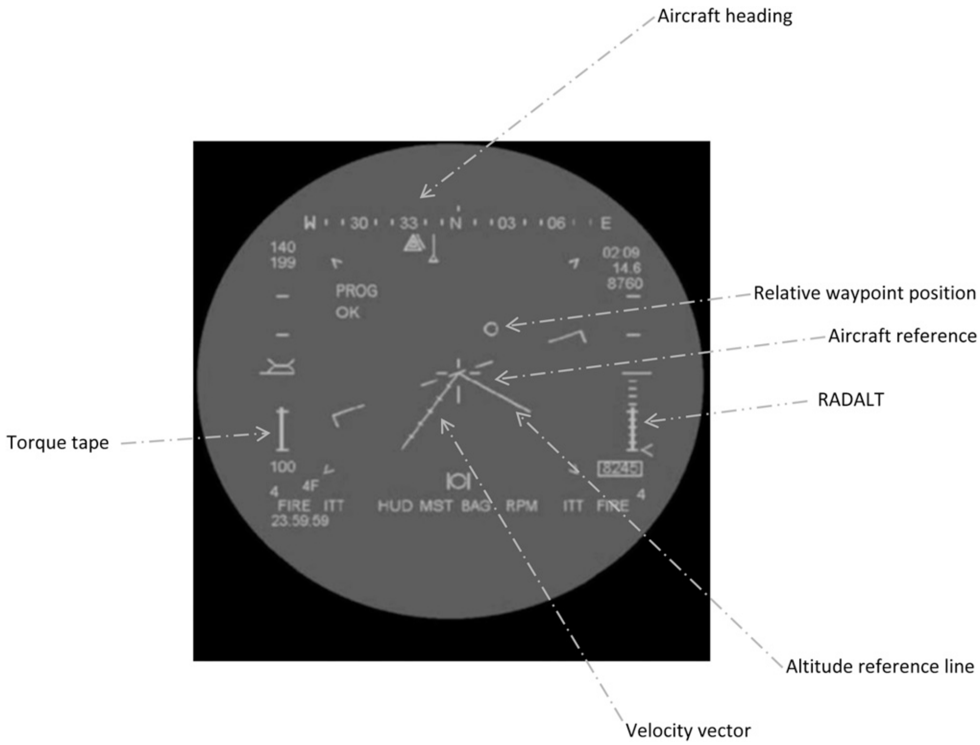

Fig. 2. A simplified version of the transition page of the CH146 AN/AVS7 symbology display that was designed for "cruise" flight only and not for departure, hover, and approach in DVE.

forward view symbology is configured for an egocentric viewpoint (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 predetermined 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 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 (15-m) AGL hover instead of terminating on the ground. A target altitude AGL marker or "carrot" was added beside the vertical speed marker. In this study, the approach to landing mode was used for single stage approaches, while the approach to hover mode was used for two-stage departures.

HDTS

The HDTS system combined 2D symbology with a 3D virtual landing grid that was precisely geo-located at a selected landing zone (**Fig. 4**). The 2D symbology 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 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, the other pilot's LOS marker, the flight path marker (a velocity vector), and the landing zone position.

The 3D conformal symbology system provided the pilots an augmented reality system 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.[8] The 3D symbology consisted of a circular landing zone marker and landing grid with vertical towers and boxes (arranged over a 3D grid) whose size and perspective changed according to the position and motion of the pilot similar to what would be seen with real-world references. The 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. The intended 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.

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. An enhanced hybrid head tracker using a cockpit mapped electromagnetic field and integrated microelectromechanical systems inertial sensor was used in order to minimize the latency generated with respect to pilot head movements. An advanced sight and display computer 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 advanced sight and display computer also required Digital Terrain Elevation Database information, which was provided as part of the simulator model. The location of the LP was entered manually in the simulator or the pilot could center the HUD LOS on a point on the ground and

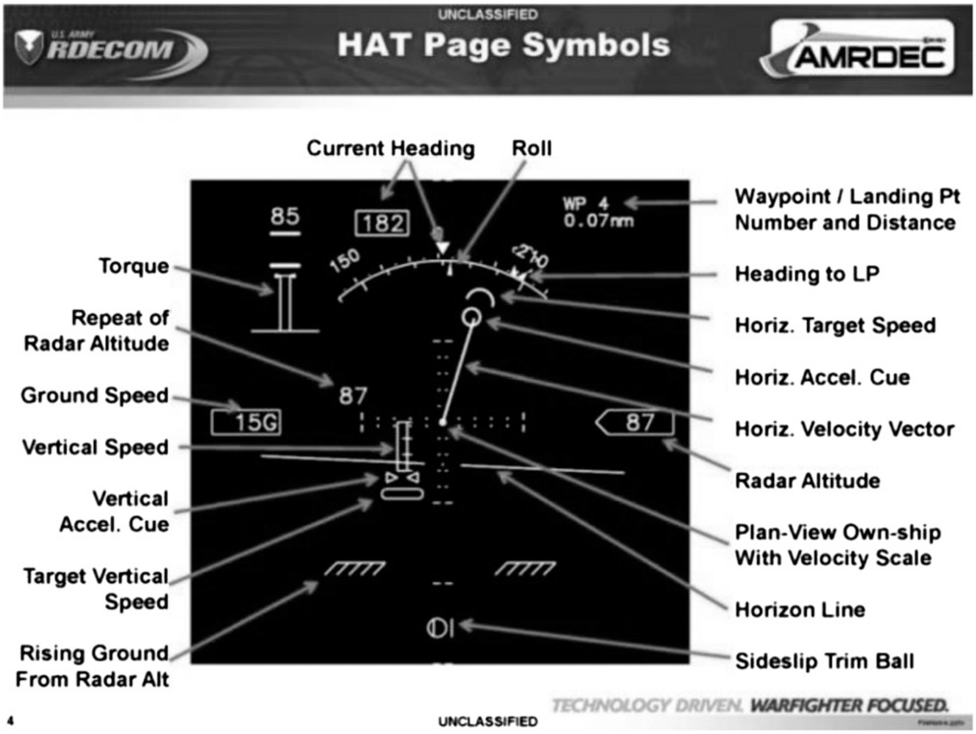

Fig. 3. The Hover/Approach/Takeoff (HAT) page symbols on approach to landing. Diagrams are taken from the DVEST Pilot Briefing for BOSS Symbology, version 13.04.04, courtesy of AMRDEC. The horizontal acceleration cue "ball" symbol represents cyclic inputs (right hand control) and the vertical acceleration "bowtie" represents collective inputs (left hand control). The horizontal target speed "cup" symbol displays 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 toward the center 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" represents 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 center of the forward view of the 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.

designate that point as the LP using the collective switch. It was also possible to redesignate the approach path direction and landing grid orientation at any time in flight.

Experimental Design

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 maneuvers for each of the three symbology systems (AVS7, HDTS, and BOSS). The five maneuvers for comparative evaluation were 1) single stage approach (landing); 2) single stage departure (takeoff); 3) two-stage approach; 4) hover turn; and 5) two-stage departure. Pilots performed the five maneuvers in the above sequence for each of the symbology system concepts, but the order of the symbology systems presented was counter-balanced across subjects using the 2-Latin square design in **Table I**. This particular design was balanced with a multiple of six subjects. Since the analysis used subjects 1-13, the 13th subject was assigned row 1. Our intention was to ensure each symbology followed the other symbology an equal number of times. Although five maneuvers were flown in the simulator, only the results of the maneuvers of primary interest are reported here; that is, the two-stage departure and the single-stage approach. This selection facilitated the comparison with those from an adjoining in-flight study where only these two specific maneuvers were evaluated due to the limited availability of flight time.

For the two-stage departure, the subject repositioned from the landing zone (LZ) at ground level to 50 ft (15 m) AGL and maintained hover (position, height, and heading) for 30 s (timed by the QTP). The QTP called for data marking and for the subject to initiate a forward transition at the end of the 30 s. The subject set forward acceleration attitude to achieve the desired airspeed and adjusted the collective to achieve the desired rate of climb. The maneuver terminated when the speed reached 40 kn. For the single-stage approach: starting at 250 ft (76 m) AGL at 80 kn and 1.3 nmi from the landing zone with heading at 305° magnetic, the subject decelerated in level flight prior to 0.8 nmi from the LZ to intercept a normal sight picture approach to the LZ at approximately 6°. The subject terminated the approach at 2–5 ft (0.6–1.5 m) above the LZ with 0 kn over the landing point. Finally the subject descended to the ground while maintaining precision position and heading. The maneuver was terminated upon touchdown.

Procedure

The test subjects were grouped into pairs and reported to the simulator at a designated date within a period of 2 wk for a 2-d session of training and data collection. They were assigned to one of the QTPs who were 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 consent form, a presimulator flight questionnaire about their flying experience (cumulative career flight hours, aircraft types), quality of their vision, general health, and history of simulator sickness. It was followed by classroom instruction on the BOSS and HDTS symbology systems by the respective system experts. Each pilot wore a flight helmet (HGU-56/P) equipped with the

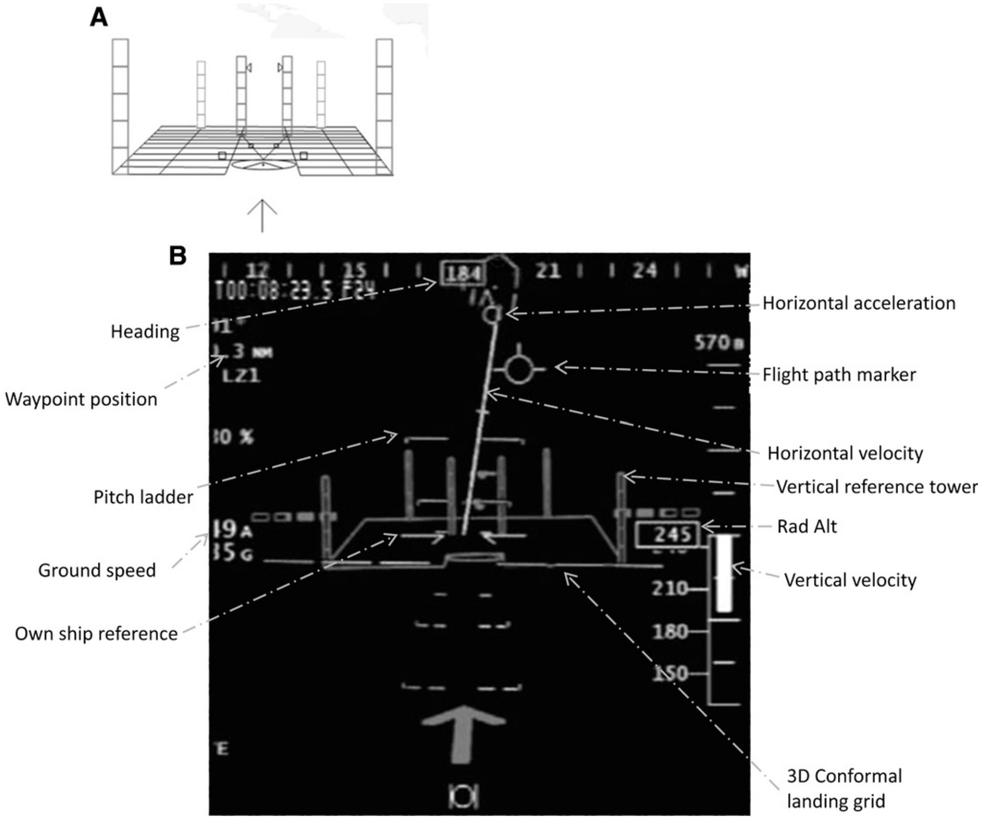

Fig. 4. A) A schematic of the 3D vertical reference towers and the horizontal grid. The landing circle was designated with an inverted Y shape. A 3D equilateral triangle attached to the inner edge of each of the two middle towers represents the aircraft's radar altitude above the LP. B) An actual screen shot of the 3D symbols displayed in DVE configuration. It employed parallel vertical and horizontal lines to provide location, height, orientation, and drift information. Specifically, the reference towers provide height orientation and drift information. Illustration taken from: Degraded Visual Environments (DVE) Landing Using HDTS, Test Flight Pilots Briefing. Courtesy of Elbit Systems Ltd., April 2013.

helmet mounted heads-up display, a head tracker, and a standard aircrew ensemble (flight suits, boots, and gloves) during the study. For each training and experimental session, the test subject of the study was in the right seat and the flight director was in the left seat.

In the afternoon of Day 1, subjects were provided with a copy of the subjective intratrial pilot questionnaire (ITPQ) and explanations for each of the rating criteria. The ITPQ consists of the China Lake Situation Awareness scale,[1] a modified Cooper Harper Workload Rating Scale[5] for mental effort, and an evaluation of subjective perceived performance. In addition, a Perceptual Cue Rating (PCR) on attitude (including roll, pitch, and yaw information), and horizontal and vertical translational rates was included.[3] These subjective scales were based on a 5-point Likert scale (where 1 = very good and 5 = very poor performance). The ITPQ also included 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.[10] 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. In addition, a list of signs and symptoms related to simulator sickness was also included in the ITPQ.

Table I. The Order of the Symbology System Concept Exposure Across Subjects.

SUBJECT	ORDER 1	ORDER 2	ORDER 3
1,7,13	AVS7	BOSS	HDTS
2,8	BOSS	HDTS	AVS7
3,9	HDTS	AVS7	BOSS
4,10	AVS7	HDTS	BOSS
5,11	BOSS	AVS7	HDTS
6,12	HDTS	BOSS	AVS7

Each pilot was given a 30-min session to become familiar with the operations of the simulator and refamiliarize themselves with the AVS7 symbology system in the simulator. The familiarization was followed by two training sessions on the BOSS (45 min each) and two training sessions on HDTS (45 min each) using the assigned flight maneuvers described above including ITPQ evaluation. In other words, each participant was given a total of 210 min (or five sessions) of training on the symbology systems in the simulator and completing associated ITPQ evaluations. 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-min training sessions in the simulator.

Data collection took place on the morning of Day 2 according to the randomized design indicated above and lasted for approximately 90 min. For each symbology system, the pilot flew each of the maneuvers twice: the first complete run through of all maneuvers served as a practice session without the ITPQ evaluation. Objective and subjective data were collected on the second run through session. Data collection was followed by postflight de-briefing in order to collect extended comments from each of the test subjects in addition to information solicited from a postflight questionnaire.

Objective test data included video recordings of the out-of-the cockpit scene with symbology overlaid, aircraft Time Space Position Information, pilot's control position, and the 2D horizontal deviation from the landing point. Flight parameters recorded during each flight in the simulator included airspeed, altitude, attitude, control column position, pedal position, trim positions, and control surface positions and collective position. From this recording, the distance to the LP, longitudinal distance and speed, lateral distance and speed, and vertical speed were taken. Deviations from pitch, roll, and heading from the initial position were calculated.

Data Analysis

To avoid any potential bias, the subjective and objective data were analyzed by two independent technical teams. The data was 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). Planned comparison was used to determine the significant differences among the three symbology system concepts (AVS7, HDTS, and BOSS). The level of alpha associated with each planned contrast was 0.05 to optimize the statistical power.

For the objective data, the format of the analysis was the same for each maneuver. Raw data was plotted for each maneuver. Each dependent variable was used in a repeated measures analysis of variance, separately for each maneuver. The dependent variables from the objective data were skewed and logged (applying logarithmic values) to achieve normalization. The minimum, median, and maximum value for each dependent variable was determined. Subsequent repeated measures analysis of variance used symbology system concepts as a factor.

RESULTS

As mentioned, only results of the two-stage departure and single-stage approach maneuvers are reported here to facilitate comparison with the results of the in-flight study (to be published). Results of the single-stage departure, two-stage approach, and hover turn will be reported elsewhere. For the simulator study, the initial analyses investigated if there was an effect of order for the three symbology system concepts. We found no evidence for an order effect. Complete data sets for the 13 subjects were used for the analysis and presented here. There were no appreciable reports of physiological signs and symptoms except one test subject, who reported minor symptoms of simulator sickness, but he was able to complete all the trials.

Subjective Measurements

Repeated measures analysis of variance (F:2,24 degrees of freedom) followed by paired comparison of symbology systems was performed on all subjective measurements for the two maneuvers. For the two-stage departure, both HDTS and BOSS demonstrated significant improvements ($P < 0.01$), i.e., increased situation awareness, lessened mental effort, and improved performance over the AVS7. Although pilots performed better when using HDTS, there was no significant difference between HDTS and BOSS in all categories. For the NASA-TLX, both HDTS and BOSS was rated significantly better ($P < 0.01$) in lessening mental demand, physical demand, temporal demand, performance, effort, frustration, and overall workload than the AVS7. However, HDTS was rated significantly better in lessening mental demand ($P < 0.05$), physical demand ($P < 0.02$), temporal demand ($P < 0.01$), efforts ($P < 0.01$), and frustration level ($P < 0.04$) over BOSS. For the PCR, both HDTS and BOSS were rated to have significant improvements ($P < 0.01$) in attitude and horizontal and vertical translational rate cues over the AVS7. HDTS provided the best cues in attitude and was significantly ($P < 0.047$) better than the BOSS. However, HDTS was not significantly different from BOSS in horizontal and vertical translational rate cueing. Only parameters with significant differences (their mean ± SEM and their corresponding p values) between the three symbology system concepts are tabulated in **Table II**.

For the single-stage approach, HDTS was rated the best for situation awareness, mental effort, and perceived performance. Specifically, the HDTS system was rated to be significantly better in situation awareness when compared with BOSS ($P < 0.03$) and the AVS7 ($P < 0.01$). For the modified Cooper-Harper rating on mental effort, HDTS was significantly better ($P < 0.05$) than the AVS7. However, although BOSS also performed better than the AVS7, it did not reach significance in all categories. For the NASA-TLX, HDTS was rated the best in all the subelements and has the lowest cumulative workload score; however, the overall workload did not show any statistical significance between the three symbology system concepts. Within the subelements, HDTS performed significantly better than the AVS7 in temporal demand ($P < 0.02$), performance ($P < 0.01$), and frustration level ($P < 0.01$), and also had lower frustration level when compared with BOSS ($P < 0.01$). There were no significant differences between BOSS and the AVS7 in all categories. For the PCR, Both HDTS and BOSS were rated to be significantly better than the AVS7 in all cueing categories ($P < 0.01$). HDTS was rated to have better attitude cueing than BOSS ($P < 0.03$), although there were no significant differences between HDTS and BOSS horizontal and vertical translational cues. Parameters with significant differences (their mean ± SEM and their corresponding P-values) between the three symbology system concepts are tabulated in **Table III**.

Objective Measurements

Repeated measures analysis of variance (F:2,24 degrees of freedom) was followed by paired comparison of symbology systems (**Table IV**). There were no 0 values obtained for any of the dependent variables, therefore all variables were logged for analysis. During the two-stage departure the Heading Error was calculated at the end of the trial (when the pilot reached 100 ft/30.5 m) from the initial position (when he was at 3 ft/0.9 m). Distance was calculated from initial position to the takeoff point before the pilot initiated forward transition after 30 s of hovering. Altitude used was 30 s from the takeoff point. Both HDTS and BOSS performed significantly ($P < 0.05$) better than the AVS7, as they were able to minimize the distance to initial position [heading root mean square error (RMSE), distance RMSE, and altitude RMSE]. However, only HDTS was

Table II. Subjective Response from the Two-Stage Departure.

	HDTS (1.81 ± 0.19) > AVS7 (3.23 ± 0.25)	$P < 0.01$
Situation awareness (China lake)	BOSS (2.26 ± 0.23) > AVS7 (3.23 ± 0.25)	$P < 0.01$
Mental workload (Cooper Harper)	HDTS (3.92 ± 0.39) > AVS7 (6.08 ± 0.42)	$P < 0.01$
	BOSS (4.46 ± 0.30) > AVS7 (6.08 ± 0.42)	$P < 0.01$
Subjective performance	HDTS (2.29 ± 0.20) > AVS7 (3.76 ± 0.15)	$P < 0.01$
	BOSS (2.67 ± 0.21) > AVS7 (3.76 ± 0.15)	$P < 0.01$
Attitude cueing	HDTS (1.66 ± 0.23) > BOSS (2.31 ± 0.23)	$P < 0.01$
	BOSS (2.31 ± 0.23) > AVS7 (3.38 ± 0.25)	$P < 0.01$
	HDTS (1.66 ± 0.23) > BOSS (2.31 ± 0.23)	$P < 0.047$
Horizontal translational rate	HDTS (1.94 ± 0.28) > BOSS (2.23 ± 0.22)	$P < 0.01$
	BOSS (2.23 ± 0.22) > AVS7 (3.40 ± 0.24)	$P < 0.01$
Vertical translational rate	HDTS (1.75 ± 0.23) > BOSS (2.34 ± 0.26)	$P < 0.01$
	BOSS (2.34 ± 0.26) > AVS7 (3.81 ± 0.28)	$P < 0.01$
NASA-TLX overall score	HDTS (7.98 ± 2.01) > BOSS (10.36 ± 1.49)	$P < 0.01$
	BOSS (10.36 ± 1.49) > AVS7 (13.51 ± 2.09)	$P < 0.01$
NASA-TLX mental demand	HDTS (9.80 ± 1.11) > BOSS (12.51 ± 0.84)	$P < 0.01$
	BOSS (12.51 ± 0.84) > AVS7 (15.16 ± 0.79)	$P < 0.01$
	HDTS (9.80 ± 1.11) > BOSS (12.51 ± 0.84)	$P < 0.048$
NASA-TLX physical demand	HDTS (7.74 ± 1.01) > AVS7 (11.87 ± 1.41)	$P < 0.01$
	BOSS (9.93 ± 0.96) > AVS7 (11.87 ± 1.41)	$P < 0.051$
	HDTS (7.74 ± 1.01) > BOSS (9.93 ± 0.96)	$P < 0.016$
NASA-TLX temporal demand	HDTS (7.20 ± 0.91) > AVS7 (11.95 ± 1.21)	$P < 0.01$
	HDTS (7.20 ± 0.91) > BOSS (9.71 ± 0.93)	$P < 0.01$
NASA-TLX performance	HDTS (7.76 ± 1.03) > BOSS (9.13 ± 1.13)	$P < 0.01$
	BOSS (9.13 ± 1.13)> AVS7 13.75 ± 1.08)	$P < 0.01$
NASA-TLX effort	HDTS (9.43 ± 1.23) > AVS7 (15.01 ± 0.89)	$P < 0.01$
	BOSS (12.31 ± 0.89) > AVS7 (15.01 ± 0.89)	$P < 0.01$
	HDTS (9.43 ± 1.23) > BOSS (12.31 ± 0.89)	$P < 0.01$
NASA-TLX frustration	HDTS (5.93 ± 0.77) > AVS7 (13.36 ± 1.21)	$P < 0.01$
	BOSS (8.58 ± 0.90) > AVS7 (13.36 ± 1.21)	$P < 0.01$
	HDTS (5.93 ± 0.77) > BOSS (8.58 ± 0.90)	$P < 0.04$

">" indicates better situation awareness, less mental workload, better subjective performance, better attitude, horizontal translational rate and vertical translational rate cueing, and better NASA-TLX overall index, less mental, physical, and temporal demand, less effort and frustration, respectively.

able to significantly provide ($P < 0.05$) the least heading error than BOSS and the AVS7. HDTS also achieved a lower heading RMSE and a lower distance RMSE than BOSS, but they did not reach statistical significance.

During single-stage approach, all performance measurements were at touchdown = 3 ft (0.9 m) except for Approach Heading RMSE and Approach Time from 50 ft (15 m) to 3 ft (0.9 m). Both HDTS and BOSS reduced the touch-down distance to the designated landing point significantly ($P < 0.05$); although HDTS performed much better than BOSS, the difference did not reach significance. However, the absolute lateral distance to the landing point was significantly ($P < 0.05$) shorter in HDTS than BOSS and the AVS7. Both HDTS and BOSS reduced the longitudinal and lateral speed significantly ($P < 0.05$), although there was no difference between HDTS and BOSS. HDTS attained the best vertical speed and

Table III. Subjective Response from the Single-Stage Approach.

Situation awareness (China lake)	HDTS (1.77 ± 0.19) > AVS7 (2.96 ± 0.31)	$P < 0.01$
Mental workload (Cooper Harper)	HDTS (1.77 ± 0.19) > BOSS (2.37 ± 0.17)	$P < 0.034$
	HDTS (4.08 ± 0.43) > AVS7 (5.27 ± 0.37)	$P < 0.01$
Subjective performance	HDTS (2.50 ± 0.28) > AVS7 (3.40 ± 0.21)	$P < 0.01$
Attitude cueing	HDTS (1.77 ± 0.20) > AVS7 (2.84 ± 0.30)	$P < 0.01$
Horizontal translational rate	HDTS (1.77 ± 0.20) > BOSS (2.35 ± 0.25)	$P < 0.03$
	HDTS (2.06 ± 0.24) > AVS7 (3.44 ± 0.19)	$P < 0.01$
	BOSS (2.61 ± 0.23)> AVS7 (3.44 ± 0.19)	$P < 0.01$
Vertical translational rate	HDTS (2.02 ± 0.25) > AVS7 (3.52 ± 0.24)	$P < 0.01$
	BOSS (2.23 ± 0.20) > AVS7 (3.52 ± 0.24)	$P < 0.01$
NASA TLX temporal demand	HDTS (8.27 ± 0.88) > AVS7 (10.7 ± 0.92)	$P < 0.025$
NASA TLX performance	HDTS (8.00 ± 1.17) > AVS7 (11.86 ± 1.16)	$P < 0.01$
NASA TLX frustration	HDTS (5.70 ± 1.05) > AVS7 (10.61 ± 1.16)	$P < 0.01$
	HDTS (5.70 ± 1.05) > BOSS (9.75 ± 0.89)	$P < 0.013$

">" indicates better situation awareness, less mental workload, better subjective performance, better attitude, horizontal translational rate and vertical translational rate cueing, and better NASA TLX overall index, less mental, physical, and temporal demand, less effort and frustration, respectively.

Table IV. Objective Results of the Two-Stage Departure and Single-Stage Approach.

	AVS7	BOSS	HDTS	STATISTICAL SIGNIFICANCE AT $P < 0.05$
Two-Stage Departure				
Heading error (degrees)	13.7 ± 3.4	7.1 ± 3.2	3.8 ± 1.9	Only HDTS was significantly different from AVS7
Distance to initial (ft)	164.9 ± 3.0	20.5 ± 10.2	19.8 ± 10.0	Both HDTS and BOSS were significantly different from AVS7
Heading RMSE (degrees)	19.5 ± 1.4	7.2 ± 1.5	4.7 ± 1.2	Both HDTS and BOSS were significantly different from AVS7
Distance RMSE (ft)	110.8 ± 4.2	26.7 ± 6.2	21.4 ± 5.4	Both HDTS and BOSS were significantly different from AVS7
Altitude RMSE (ft)	16.7 ± 2.3	6.5 ± 3.2	6.4 ± 3.3	Both HDTS and BOSS were significantly different from AVS7
Single-Stage Approach				
Distance to LP (ft)	90.4 ± 8.4	27.8 ± 10.2	18.9 ± 8.2	Both HDTS and BOSS were significantly different from AVS7
Absolute longitudinal distance to LP (ft)	42.1 ± 2.2	6.5 ± 1.3	2.3 ± 0.7	Both HDTS and BOSS were significantly different from AVS7
Vertical speed ($ft \cdot s^{-1}$)	205.0 ± 12.4	214.1 ± 12.3	128.3 ± 13.1	HDTS was significantly different from BOSS and AVS7
Approach heading RMSE (degrees)	5.3 ± 1.1	8.1 ± 1.2	3.2 ± 1.1	HDTS was significantly better than BOSS and AVS7. BOSS performed worse than AVS7

performed significantly ($P < 0.05$) better than the AVS7 and BOSS. Similarly, HDTS was able to minimize heading error significantly compared to the other two systems and the RMSE for the approach heading was significantly ($P < 0.05$) less than AVS7 and BOSS, while the RMSE for approach heading in BOSS was the highest ($P < 0.05$). There were no significant differences observed among the three symbology system concepts in longitudinal speed, lateral speed, pitch, absolute roll, heading error, and approach time.

DISCUSSION

The main finding from this simulator study demonstrated that in general, both the HDTS and BOSS systems performed better than the AVS7 symbology system. It is not a surprising finding that the AVS7 symbology system is inadequate for operations in DVE, as it was not designed for operations in DVE and it does not possess a specific cueing set for approach or departure in DVE. It should also be noted that the AVS7 was not designed to be used as primary flight instrumentation. In the two-stage departure, HDTS was rated significantly better in lessening effort, attaining lower frustration level, and lessening mental, physical, and temporal demand. HDTS also provided significantly better perceptual cues in attitude, which includes roll, pitch, and yaw information. This subjective evaluation was further confirmed by the flight performance data showing that HDTS achieved significantly least heading error. Similarly, in the single-stage approach, HDTS was rated the best (statistically significant) in situational awareness and rated the best in all the subelements of the NASA-TLX. HDTS also provided the best (statistically significant) attitude cueing. The flight performance data demonstrated that HDTS attained the best vertical speed and was able to minimize heading error significantly. It should also be noted that RMSE for the approach heading was highest in the BOSS. Although the AVS7 does not possess a specific cueing set for approach in DVE, as stated above, all the pilots had more experience in using the AVS7 system and it appears that they were able to compensate for the lack of specific cueing. It is possible that with more training the performance with the BOSS system could have been improved.

Without reliable external visual references that provide essential orientation information, subthreshold lateral drifts (along the horizontal plane) cannot be detected by the vestibular system. Therefore, undetected drift is a serious problem during DVE departure and approach. Our data suggested that both HDTS and BOSS were able to minimize heading error and heading RMSE in the two-stage departure. However, during the single-stage approach, only HDTS was able to minimize the lateral drift most effectively (as demonstrated by least approach heading RMSE, least absolute lateral distance to landing point). Subjectively, 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 weaknesses relative to one another and they are discussed below.

The approach guidance strategy was rated as the best feature among the three symbology concepts, especially in the two-stage approach. Our flight performance 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 consensus from the subjective questionnaire and postflight questionnaire and interviews suggested that the BOSS symbols were not necessarily intuitive during takeoff, hover, and 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 that relates to the fact that information was presented with reference to the external world. For example, horizontal velocity was indicated with respect to self (own ship). However, the heading arc providing yaw information was based on how the world was 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; thus, pilots often lose track of the heading when paying attention to other elements lower in their FOV within the symbology.

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: radar altimeter, rising ground, target altitude cue, and radar altimeter repeater (near the vertical speed cue). Although each indicator was useful for its own purpose, there was too much effort required to interpret them all. During the two-stage departure, when concentrating on the drift vector, at times pilots failed to recognize the 50-ft (15-m) 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.

Our objective results indicated that in both maneuvers, heading drifts were quite noticeable when using AVS7 and BOSS. The heading tape in BOSS 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 redirect 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. 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 and execute correction. In addition, time spent to repeatedly crosscheck 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 situational awareness breaking down. With time, the frustration level increased, workload increased, pilots became overwhelmed with the task, and fatigue set in.

The pairing of egocentric formatted symbology with imagery (generated on board the aircraft) in a forward-looking viewpoint allows for conformal (or scene-linked) symbology and creates the perception that the symbology is referencing the actual outside visual scene. McCann and Foyle[11] reported that conformal symbology allows for concurrent processing between the imagery information and symbology information. In general, our data suggests that HDTS performed the best in both maneuvers flown in the simulator. 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 min in total), most pilots were surprised that they could fly and land using the HDTS system with little difficulty in DVE.

Consensus of postflight interviews suggested that the HDTS symbology system concept provided good situational awareness when hovering over the landing zone due to the availability of crucial orientation cues (the earth-referenced 3D grid) of the aircraft during DVE. Specifically, the altitude reference (vertical towers and track bars) was visible at all times and made it easy to detect movement as it provided a natural way that enabled pilots to make corrections 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 redesignation capability provided by HDTS would be advantageous during unanticipated DVE.

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 shallowly and slow down early, "dragging the approach in," so that they could take full advantage of the grid upon arrival at that point. To some pilots, the movement of the nonconformal 2D symbols relative to the 3D grid could induce a false sense of aircraft attitude change. It is also possible that the use of conformal symbology could change 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 a false sense of motion due to the perception of the conformal landing grid moving in response to the head tracker. Training and experience in using HDTS would minimize this effect.

In conclusion, when the conformal symbology system (HDTS) possesses the accuracy and consistencies of the registration against the real world, it allows pilots to depart and approach when external visual cues are unavailable. The concept appears to be more suitable for legacy platforms with conventional flight control systems. A low-speed symbology system (BOSS) consisting of 2D graphical elements that provide scaled indication of acceleration, velocity vector, drift, ground speed, rate of descent, and rate of closure toward a preplanned LP was demonstrated to be more effective than the current AVS7, but less effective than HDTS.

There are a number of limitations in this simulation investigation: for example, it is a fixed based simulator. The limited adjustability of the cockpit might have presented some biomechanical issues with some subjects. In addition, an artificial situation was created that was more difficult than real life flying. The capability and performance of the HDTS and BOSS in flight during DVE will be discussed in a subsequent article.

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