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

Bob Cheung; Gregory Craig; Brad Steels; Robert Sceviour; Vaughn Cosman; Sion Jennings; Peter Holst

BACKGROUND: During approach and departure in rotary wing aircraft, a sudden loss of external visual reference precipitates spatial disorientation.

METHODS: There were 10 Royal Canadian Air Force (RCAF) Griffon pilots who participated in an in-flight investigation of a 3-dimensional conformal Helmet Display Tracking System (HDTS) and the BrownOut Symbology System (BOSS) aboard an Advanced System Research Aircraft. For each symbology system, pilots performed a two-stage departure followed by a single-stage approach. The presentation order of the two symbology systems was randomized across the pilots. Subjective measurements included situation awareness, mental effort, perceived performance, perceptual cue rating, NASA Task Load Index, and physiological response. Objective performance included aircraft speed, altitude, attitude, and distance from the landing point, control position, and control activity. Repeated measures analysis of variance and planned comparison tests for the subjective and objective responses were performed.

RESULTS: For both maneuvers, the HDTS system afforded better situation awareness, lower workload, better perceptual cueing in attitude, horizontal and vertical translation, and lower overall workload index. During the two-stage departure, HDTS achieved less lateral drift from initial takeoff and hover, lower root mean square error (RMSE) in altitude during hover, and lower track error during the acceleration to forward flight. During the single-stage approach, HDTS achieved less error in lateral and longitudinal position offset from the landing point and lower RMSE in heading.

DISCUSSION: In both maneuvers, pilots exhibited higher control activity when using HDTS, which suggested that more pertinent information was available to the pilots. Pilots preferred the HDTS system.

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

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In degraded visual environments (DVE), without reliable external visual references on the rate of closure, drifts, and altitude during the critical phases of flight (departure, hover, and approach), pilots may succumb to spatial disorientation (SD) and subsequently make undesirable control inputs that could lead to fatality. Other contributing factors for SD include uncertain and erroneous perception of the direction of motion during oscillatory gravitational acceleration along the spinal axis of the body.[12,13] In addition, subthreshold lateral and longitudinal drifts (along the horizontal plane) cannot be detected by the vestibular system. 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 known as linear vection or circular vection depending on the direction of visual motion of the blowing sand and snow. The sudden loss of external visual references would necessitate the transition from visual meteorological conditions (VMC) to instrument meteorological conditions (IMC) flying. During the transition, there is a latency to reacquire orientation cues.[3,4] This latency would increase in an unanticipated encounter with DVE. Therefore, symbology system concepts that will be useful for DVE should possess intuitive lateral, longitudinal, and vertical translational cues, as well as reliable altitude references. Our previous investigation[5] in the

From Defence Research and Development Canada, Toronto Research Centre, Toronto, Ontario, Canada.

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Address correspondence to: Bob Cheung, Ph.D., M.Sc., DRDC Toronto Research Centre, 1133 Sheppard Ave. W., Toronto, Ontario M3K 2C9, Canada; bob.cheung@utoronto.ca or bob.cheung@drdc-rddc.gc.ca.

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simulator suggested that although both the Helmet Display Tracking System (HDTS) and the BrownOut Symbology System (BOSS) were found to be more useful than the Royal Canadian Air Force (RCAF) CH146 AN/AVS7 symbology system in DVE, pilots performed better when using HDTS than the BOSS system and is the pilots' preferred flight display. In this study we advanced our investigation on the effectiveness of HDTS and BOSS in flight during DVE.

METHODS

Subjects

Of the thirteen RCAF rotary wing male operational pilots who participated in the simulator study, 10 served as subjects for the in-flight study. They had accumulated between 550 to 4900 h of flying time (mean 1911 ± SEM 401.72 h) on the helicopter and experience in day heads-up display (HUD). The study was approved by the DRDC Human Ethics Committee (2013-031) and all subjects gave written informed consent. During training when flying under the hood, one subject experienced a strong sensation of spinning while observing the BOSS symbology and exhibited some symptoms of motion sickness, specifically queasiness. Further investigation suggested that the disorientation experienced was not dependent on the symbology system that was used, but occurred whenever the blind flying hood was down. His participation in the flight study was discontinued after 24 min and his data was omitted in the final analysis. Therefore, the final results of this study were based on nine operational pilots.

Experimental Design

A within-subject repeated measures design was employed. In order to simulate DVE during a two-stage departure and single-stage approach, a custom light-proof blind flying hood 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 maneuvers using symbologies displayed by the Day Display Module (Elbit Systems Ltd, Haifa, Israel) with a safety pilot in the right seat. When the hood was in the down position, it completely obscured the pilot's external vision (**Fig. 1**). In-flight investigation took place on the National Research Council (NRC) Advanced System Research Aircraft (ASRA, C-FPGV). The side window and the chin bubble of the left seat in the ASRA were also occluded. The order of presentation of the two symbology systems was counterbalanced across subjects.

Equipment

The National Research Council ASRA is a modified Bell 412HP helicopter. By comparison, the RCAF CH146 Griffon is a militarized variant of the Bell 412. For the flight trial the ASRA used a modified experimental fly-by-wire (FBW) control system. Under this paradigm, one can tune the aircraft to fly with a wide variety of control systems such as rate-type response (pitch/roll/yaw rates in proportion to control inputs), attitude response

Fig. 1. The blind flying hood attached to the flight helmet (completely obscured the subject's external vision), with the subject seated in the left seat of the NRC ASRA.

(attitude in proportion to control inputs), and translational rate-type response (translational rate of movement in proportion to control inputs) with the option of attitude, height, or heading hold in conjunction with these various modes. For this in-flight investigation, the ASRA was assessed and configured by a RCAF qualified test pilot (QTP) and a Griffon operational pilot. The handling qualities of the FBW attitude hold control model adequately represented the RCAF Griffon CH146 in terms of pilot control technique and workload for the basic flight maneuvers that were investigated. In addition, a navigation pallet provided an embedded global positioning system (GPS)/inertial navigation system (INS) and other aircraft parameters via a data-bus were integrated onto the ASRA. The HDTS and BOSS symbology systems were integrated into this data-bus.

Symbology System Concepts

Based on the lessons learned from our simulator investigation,[5] a number of changes to the HDTS and BOSS symbology systems were implemented for the flight trial.

BOSS. The hover/approach/takeoff page was used and recommended changes that were implemented for the flight trial included the following items. A heading error tape was added and was set to appear when the aircraft was below 10 kn and when the heading error was greater than 3°. Pilots were instructed to use the tail rotor pedals to "step on the tape" to correct the errors. A heading "bug" was added on the heading tape to provide a reference to the pilots during the two-stage departure (**Fig. 2**). The heading numeric box above the heading tape was relocated to the right of center for the flight trial.

HDTS. A number of minor changes were made in the 2D elements to improve readability such as improving waypoint name, embedded global positioning system/inertial navigation system (EGI) status messages, shape and scale of the pitch ladder, landing zone marker, and adjustable brightness and halo of

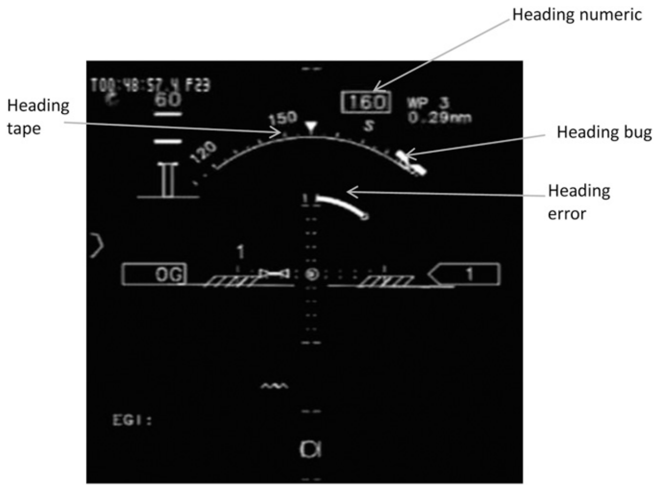

Fig. 2. An actual screen shot of the heading error tape which was user selectable when the heading error is more than 3° (BOSS symbology system version 13.06.26).

the 3D elements. The 3D elements of the HDTS used for the flight trial were identical to those used in the simulator investigation with the following changes (**Fig. 3**). The shape of the virtual radar altimeter (RADALT) was changed from a triangular pointer to a square ring around the towers. A new triangular symbol on towers was used to show virtual vertical speed with respect to virtual RADALT. Precision approach path indicators were used to help maintain the glide slope by having four horizontal rectangles. If the aircraft was on the correct glide slope, two of the four horizontal rectangles would be filled. A new "Parking" symbol shown as a "guiding (dynamic) caret"; aligned the aircraft with the static caret and ensured the aircraft arrived at the designated landing point. The guiding caret allowed for the determination of horizontal drift.

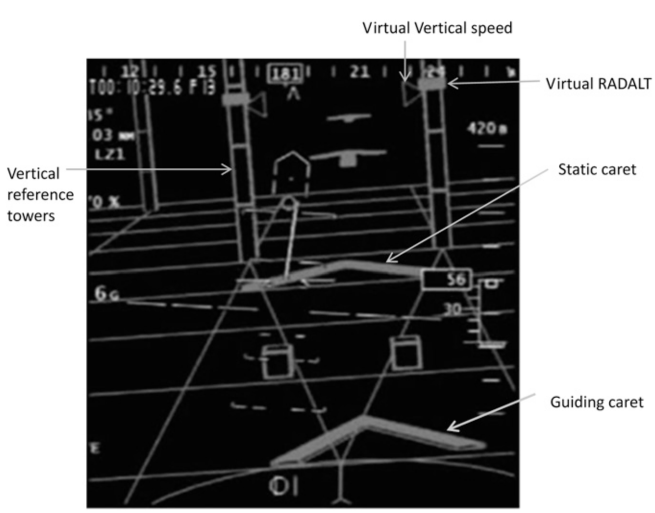

Fig. 3. An actual screen shot of the HDTS 3D conformal symbology system during the final approach showing the guiding (dynamic) caret, static caret, virtual radar altimeter (RADALT), virtual vertical speed, and virtual vertical reference towers.

Procedure

Day 1—classroom instruction and in-flight training. A pair of test subjects received a revision and update briefing on the two symbology system concepts in the morning followed by familiarization and training flights on the ASRA in the afternoon. The revision and updates on the HDTS symbology system were 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 departure and approach 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 and for the approach. Prior to the training flight, the subjects had an opportunity to practice on the controls of the HDTS and the alignment of the HUD in the aircraft hangar. Both subjects were on board the aircraft for each training flight. The nonflying subject sat in the back cabin seating to view the symbology on a laptop computer. Each pilot received approximately 45 min of flight training for each of the symbology systems. The total duration of training for each subject lasted between 90 to 96 min.

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 would 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 display and the time when the subject was given control on each symbology set were recorded. For each maneuver, the subjects were afforded three trials for each symbology system. The data collection flight lasted approximately 72 min for each subject.

Subjective Measurements

Identical to the simulator study, subjects were asked to provide ratings on a number of human factors issues related to their performance between trials. The intratrial pilot questionnaire consisted of the China Lake Situation Awareness scale,[1] a modified Cooper Harper Workload Rating Scale,[6] and an evaluation of subjective performance based on a 5-point Likert scale. In addition, subjects were asked to assess their perceptual cue rating on attitude (including roll, pitch, and yaw information), and horizontal and vertical translational rates. 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.[9] 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 postflight subjective report was administered followed by discussion on their relative performance with the QTP and the principal investigator.

Objective Measurements

Flight parameters recorded during each flight included airspeed, altitude, attitude, cyclic position, pedal position, force trim release activity, and collective position. From this recording, the distance to the designated landing point (LP), longitudinal distance and speed, lateral distance and speed, vertical speed, pitch, roll, and heading error from initial position were calculated. Depending on the specific maneuver, different dependent variables for the objective assessment of performance were used, including airspeed, altitude, attitude, control column position, pedal position, trim positions, control surface position, and collective position.

Data Analysis

For consistency across subjects, the two-stage departure was divided into three phases: Phase 1 (takeoff phase) was from subject engagement until the helicopter first crossed the "mixed height = 50 ft." Phase 2 (hover phase) was the 50 ft. hover, and Phase 3 (acceleration phase) was the "departure proper" following the hover. The single-stage approach was divided into two phases: Phase 1 was between 0.7 nmi and 0.4 nmi distance from the landing point. Phase 2 was between 0.4 nmi from the landing point and the end of engagement. These metrics were chosen because 0.7 nmi typically denotes the time when the subject took control, and 0.4 nmi typically denotes the time when the blind flying hood was lowered. If the pilot took control closer than 0.7 nmi from the landing point, the first available distance was used as the starting index.

To avoid any potential bias, the subjective and objective data were analyzed by two independent technical teams. Experimental data were stored and backed up after the completion of each subject test trial; data were double-keyed and compared for incompatible fields that were checked and corrected. The data were reviewed for consistency, plausibility, and out-of-range values. The subjective data were analyzed using Statistica (StatSoft Inc., Tulsa, OK), using repeated-measures analysis of variance. Planned comparison was used to determine the significant differences between the two symbology system concepts. 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. Each dependent variable was used in a repeated measures analysis of variance (F:1, 8 degrees of freedom), separately for each maneuver. Initial analyses was performed to investigate if there was an effect of order for the two symbology system concepts. Due to the variability in performance across pilots, for those performance measurements that were more than 2 SDs from the average, we defined those as outliers. In addition, those events were handled differently by different safety pilots. Specifically, the safety pilot normally would have re-engaged the evaluation pilot to allow him to complete the maneuver. This did happen in some of the flights, which made the testing procedure for those flight trials inconsistent with all of the remaining flights. Therefore, the results are presented with and without the outliers.

In addition to the above analysis, we also employed the Dynamic Interface Modeling and Simulation System (DIMSS), which is a documented means of assessing the control activity/workload.[14] This method considered a control deflection metric (size of control movement) and a control reversal metric (a minimum or maximum in the control deflection time history) that represent the amplitude and frequency of control movements, respectively. Essentially the activity metric was calculated by multiplying the number of control reversals by the SD (of the amplitude) of control deflections within a moving 3-s window. A higher DIMSS score suggested a higher level of control activity. In our analysis, high frequency control inputs (above 3.3 Hz) were filtered out as they are unlikely to be pilot control inputs and were not considered to reflect pilot's control activity. For our calculations, we also set a minimum deflection size (at 0.02 in) in order to remove control sensor noise. We also employed 3D error plots in order to accommodate two cases where the data files ended with the pilot 50-60 ft above the landing position, but there were very small lateral or longitudinal offsets. That is, the 2D error was small, but it was obviously not representing the entire flight trial record. Overall, the vertical component (height) in the 3D error was small.

RESULTS

There were a number of mild episodes of disorientation when the blind flying hood was down (one when using HDTS and five when using BOSS out of a total 54 trials). However, the sensation did not persist and the subjects were able to complete all the trials.

Subjective response. Repeated measures analysis of variance (F: 1, 8 degrees of freedom) was followed by paired comparison of the two symbology system concepts. There was no order effect between the three trials. There was no significant difference between the three trials within the same maneuver using the same symbology system. Planned comparison post hoc tests were used to determine the significant differences between the two symbology system concepts within each trial of the three successive trials. For the two-stage departure, the HDTS system provided better situation awareness, required significantly less mental effort, and obtained better subjective performance. However, it did not reach statistical significance in subjective performance. Similarly HDTS provided better attitude, horizontal (lateral and longitudinal) translational rate, and vertical translational rate cueing. HDTS required significantly less overall workload ($P < 0.01$) based on the NASA-TLX questionnaire. However, it did not reach statistical significance in physical demand, temporal demand, or frustration level. Details of the subjective results and their respective statistical significance for each category and trials are tabulated in **Table I**.

Similarly in the single-stage approach, HDTS required the least mental effort and provided better situation awareness, and

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

Situation awareness (China lake)	HDTS > BOSS in all 3 trials	Significantly different in 1 trial, $P < 0.023$
Mental workload (Cooper Harper)	HDTS > BOSS in all 3 trials	Significantly different in all 3 trials, $P < 0.026$, $P < 0.019$, $P < 0.014$, respectively
Attitude cueing	HDTS > BOSS in all 3 trials	Significantly different in all 3 trials, $P < 0.001$, $P < 0.01$, $P < 0.04$, respectively
Horizontal translational rate	HDTS > BOSS in all 3 trials	Significantly different in 2 trials, $P < 0.023$, $P < 0.041$, respectively
Vertical translational rate	HDTS > BOSS in all 3 trials	Significantly different in 1 trial, $P < 0.017$
NASA-TLX overall score	HDTS > BOSS in all 3 trials	Significantly different in all 3 trials, $P < 0.01$, $P < 0.01$, $P < 0.01$, respectively
NASA-TLX mental demand	HDTS > BOSS in all 3 trials	Significantly different in all 3 trials, $P < 0.05$, $P < 0.01$, $P < 0.02$, respectively
NASA-TLX performance	HDTS > BOSS in all 3 trials	Significantly different in 1 trial, $P < 0.016$
NASA-TLX effort	HDTS > BOSS in all 3 trials	Significantly different in 2 trials, $P < 0.001$. $P < 0.026$, respectively

> 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, and less effort and frustration, respectively.

achieved better perceived performance over BOSS. The NASA-TLX overall workloads for HDTS was significantly lower ($P < 0.05$) than the BOSS system. However, it did not reach statistical significance in temporal demand or frustration level. Details of the results and their respective statistical significance for each category and trials are tabulated in **Table II**.

Objective response. Initial analysis indicated that there was no evidence of an order effect for the two symbology system concepts (F-test not statistically significant). Similar to the subjective response there were no significant differences between the three trials within each symbology system. For the objective data, we combined the results of the three test trials within each maneuver. Therefore, the only factor that was considered was the symbology systems (HDTS vs. BOSS).

For the two-stage departure, the HDTS performed better (less error) than BOSS. However, it did not reach statistical significance in the root mean square error (RMSE) longitudinal distance from initial takeoff and hover, in RMSE distance error from initial takeoff and initial hover, RMSE altitude and heading for the entire maneuver, and control activity as measured by the total time when force trim release was depressed during takeoff. In general, the employment of HDTS in the two-stage departure afforded less error as demonstrated by smaller RMSE for lateral distance from initial hover position, smaller RMSE in altitude during hover, and smaller track error during the acceleration phase of the departure. In addition, there was an increased control activity during hover and final departure. It appears that HDTS provided readily available orientation information, and hence increased control activity. The performance of the HDTS vs. the BOSS system and their respective levels of statistical significance are tabulated in **Table III**.

For the single-stage approach, 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. There was no difference between HDTS and BOSS in pitch and roll attitude and force trim release during Phase 1 and Phase 2 of the maneuver. In addition, there was no difference in the average offset (longitudinal difference) from desired landing position. Although HDTS achieved less error than BOSS in vertical, longitudinal, and lateral speed at touchdown, and less touchdown heading error, less approach time from 50 ft and less approach time from 30 kn to touchdown, they did not reach statistical significance. The outlier's data rendered the average offset in lateral and longitudinal distance from the desired landing position in 2D distance from the landing point to be statistically not significant. Similarly, the outlier's data rendered the average offset in lateral and longitudinal distance from the desired landing position in 3D distance from the landing point to be statistically not significant. Detailed performance of the HDTS vs. the BOSS systems during single-stage approach and their respective level of significant differences are tabulated in **Table IV**.

DISCUSSION

When the pilot is provided with intuitive and salient information, the pilot's overall situation awareness of the aircraft orientation increases and the decision making process for controlling the

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

Situation awareness (China lake)	HDTS > BOSS in all 3 trials	Significantly different in 2 trials, $P < 0.01$, $P < 0.01$, respectively
Mental workload (Cooper Harper)	HDTS > BOSS in all 3 trials	Significantly different in 2 trials, $P < 0.01$, $P < 0.045$, respectively
Subjective performance	HDTS > BOSS in all 3 trials	Significantly different in 1 trial, $P < 0.017$, respectively
Attitude cueing	HDTS > BOSS in all 3 trials	Significantly different in all 2 trials, $P < 0.01$, $P < 0.012$, respectively
Horizontal translational rate	HDTS > BOSS in all 3 trials	Significantly different in 2 trials, $P < 0.036$, $P < 0.023$, respectively
Vertical translational rate	HDTS > BOSS in all 3 trials	Significantly different in 1 trial, $P < 0.028$
NASA-TLX overall score	HDTS > BOSS in all 3 trials	Significantly different in all 3 trials, $P < 0.01$, $P < 0.01$, $P < 0.01$, respectively
NASA-TLX mental demand	HDTS > BOSS in all 3 trials	Significantly different in all 1 trial, $P < 0.011$
NASA-TLX physical demand	HDTS > BOSS in all 3 trials	Significantly different in 1 trial, $P < 0.021$
NASA-TLX performance	HDTS > BOSS in all 3 trials	Significantly different in 1 trial, $P < 0.023$
NASA-TLX effort	HDTS > BOSS in all 3 trials	Significantly different in 2 trials, $P < 0.042$. $P < 0.042$, respectively

> 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, and less effort and frustration, respectively.

Table III. Comparative Performance of HDTS and BOSS as Reflected by Objective Response During the Two-Stage Departure.

RMSE lateral distance from initial takeoff (Phase 1)	HDTS (4.65 ± 0.65) < BOSS (7.43 ± 0.95)	$P < 0.06$
RMSE lateral distance from initial hover position (Phase 2)	HDTS (11.0 ± 0.54 < BOSS (20.65 ± 1.19)	$P < 0.018$
RMSE altitude during hover (Phase 2)	HDTS (8.43 ± 0.76) < BOSS (20.65 ± 1.19)	$P < 0.03$
Track error during acceleration phase of departure (Phase 3)	HDTS (3.25 ± 0.33) < BOSS (6.11 ± 0.59)	$P < 0.055$
Control activity during departure (Phase 3)	HDTS (2.86 ± 0.27) > BOSS (2.38 ± 0.42)	$P < 0.027$
Control activity during hover (Phase 2)	HDTS (3.00 ± 0.37) > BOSS (2.37 ± 0.27)	$P < 0.025$

< indicates less error and > indicates greater control activity.

aircraft strengthens and he can correspond with positive control inputs promptly. Therefore, for any instrument display to be useful, the guidance algorithms must drive the symbology in a timely manner so that the pilot can safely track and maintain the guidance symbols throughout the departure or approach without increasing their cognitive workload. This is especially important in DVE when external visual cues are unavailable.

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. The HDTS 3D conformal symbology system uses an augmented reality principle where symbols are placed accurately on the real world ahead of the aircraft and viewed through a helmet mounted display. It is earth referenced; it mimics real world cueing and provides perspective cues. Although both the HDTS and BOSS symbology systems possess their respective effectiveness and insufficiencies, the results of the in-flight investigations suggested that the subjects' performance was much better with HDTS during the two-stage departure and single-stage approach. In general, HDTS afforded better situation awareness, less mental effort, higher perceived performance, and better perceptual cueing for roll, pitch, and yaw attitude, and horizontal and vertical translational rate. In addition, HDTS provided a better NASA-TLX score 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 lateral and longitudinal drifts and altitude error during departure and approach. The vertical reference towers of the 3D conformal system appear to provide useful virtual vertical reference, compensating for the vestibular inadequacies that were mentioned in the introduction. Specifically, subjects were able to successfully land the aircraft 85.1% of the total landings with HDTS, an increase of almost a factor of 2 when compared to the BOSS system (with successful landings of only 45.1%).

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 single-stage 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 vs. 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 level to a different pilot. In addition, control strategies used by the pilot depend on the aggressiveness of the pilot and the pilot's perception of task performance.[11]

Based on the subjective and objective results and postflight debriefing, the HDTS symbology system was reported to be intuitive. Specifically, the conformal 3D grid in HDTS provided excellent lateral cueing during the 50-ft hover and enabled the

Table IV. Comparative Performance of HDTS and BOSS as Reflected by Objective Response During the Single-Stage Approach.

Average offset (lateral and longitudinal distance) from desired landing position in 2D with outliers	HDTS (21.07 ± 1.05) < BOSS (133.63 ± 4.36)	$P < 0.08$ (not significant)
Average offset (lateral and longitudinal distance) from desired landing position in 2D without outliers	HDTS (18.18 ± 1.05) < BOSS (133.63 ± 2.03)	$P < 0.003$
Average offset (lateral and longitudinal distance) vertical distance from desired landing position in 3D with outliers	HDTS (25.53 ± 0.84) < BOSS (138.34 ± 4.26)	$P < 0.08$ (not significant)
Average offset (lateral and longitudinal distance) vertical distance from desired landing position in 3D without outliers	HDTS (21.46 ± 1.05) < BOSS 79.42 ± 2.03)	$P < 0.003$
Average offset (lateral distance) from desired landing position with outliers	HDTS (3.49 ± 0.49) < BOSS (48.48 ± 1.07)	$P < 0.001$
Average offset (lateral distance) from desired landing position without outliers	HDTS (3.28 ± 0.49) < BOSS (42.96 ± 1.68)	$P < 0.001$
Average offset (longitudinal distance) from desired landing position without outliers	HDTS (16.88 ± 1.89) < BOSS (53.89 ± 1.92)	$P < 0.015$
RMSE heading	HDTS (4.34 ± 0.37) < BOSS (7.68 ± 0.42)	$P < 0.011$
Average heading standard deviation during phase 1	HDTS (2.06 ± 0.62) < BOSS (5.85 ± 0.95)	$P < 0.012$
Average heading standard deviation during phase 2	HDTS (2.28 ± 0.46) < BOSS (6.04 ± 2.48)	$P < 0.001$
Control activity during Phase 1 of single-stage approach	HDTS (2.55 ± 0.24) > BOSS (2.06 ± 0.26)	$P < 0.048$
Control activity during Phase 2 of single-stage approach	HDTS (4.35 ± 0.31) > BOSS (3.16 ± 0.27)	$P < 0.001$

< indicates less error and > indicates greater control activity.

pilot to correct for any lateral and heading (yaw) drifts. 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 ± 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 nmi inbound (once vertical velocity and altitude appeared on the vertical towers). This was possible because drift cues were quickly recognized with peripheral detection within their field-of-view (FOV) while scanning for primary (torque, height, and 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 FOV, for example, when wearing night vision goggles, would typically look off-axis to better perceive longitudinal drift. The vertical reference towers in the HDTS display were reported to be very useful for directional control and useful for vertical control. The changes made in the vertical speed indicator and RADALT rings in the two middle front towers were also reported to be helpful. The "tilted circle" at the center of the intended LP indicating terrain slope based on calculation from digital terrain elevation database information was reported to be 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 toward the final landing. The static and guiding/dynamic carets (parking symbols) provided 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, where 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, reposition laterally, and continue the approach. 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, head tracker (as indicated previously), and precision radar altimeter. There were no perceived latency issues with the hybrid inertial-magnetic head tracker during head movements. In general, the pilots` comments regarding the HDTS symbology system concept was positive. A sample of comments is provided below:

- HDTS, specifically the "towers," provide more comfort for the executed maneuvers;
- HDTS provided enough 3D cues such that it made for a very natural feel using typical helicopter references available during a VMC approach;
- HDTS was very useful for all tasks, but especially below translational lift (hover and fine position adjustment), the 3D reference was natural and as if I never lost visual reference;
- HDTS provides 90% of what you need on the Griffon to execute the maneuvers.

Based on the subjective and objective data and postflight pilot debriefing, it was 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. The implemented heading error indicator (arc) was found to be effective, although it added to the cluttering of the BOSS display. 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. For example, if the pilot was focusing on position accuracy, then altitude and heading, errors would appear. 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 kn), 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 toward over-controlling, especially with the BOSS system, resulting in unnecessarily large corrections. In general, BOSS required more interpretation and understanding; it also required a different control strategy (similar to instrument cross-check) than the HDTS or visual flying.

There have been numerous reports on the effectiveness of the BOSS symbology systems in brownout landings[15,16] using aircraft with heading hold capability (for example, the H60 Blackhawk). 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.[10] In addition, 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.

However, without the heading hold capability, 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.[2,10] In our study with a conventional flight control system without a heading hold, 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. Postflight comments from the participants indicated that the added requirement of interpretation in the BOSS symbology system was prone to attentional capture, resulting in the undesirable and extended perceptual fixation on certain aspects of the display, thereby disrupting normal scanning patterns, causing a loss of situation awareness. Wickens[17] suggested that while 2D symbology provides greater precision in locating spatial surroundings, it also demanded more attentional and cognitive workloads on a particular location or symbols in the display while trying to ignore the overlapping HUD imagery.

On the other hand, the 3D conformal HDTS system presents cueing for all axes using conventional visual attributes (e.g., vertical reference towers) and allowed the maintenance of the heading to within an acceptable standard. HDTS was able to accommodate dividing attention (time sharing involves the efficient allocation of attentional resources to at least two different sources of information). The subjects were able to divide their attention to the conformal runway symbol and its far domain counterpart. Similarly they were able to monitor the appearance of a far domain target while processing flight instrument information. In addition, the conformal symbology in HDTS allows efficient allocation of attentional resources to lateral, longitudinal, and vertical information during the critical phases of flight. In essence, pilots can see a (limited) representation of their position and motion with respect to the outside world with HDTS, whereas with BOSS, the pilots have to build up a mental representation of that same information.

In general, comments with respect to BOSS were less positive and can be seen from the quotes below:

- Prefer the BOSS for approach and information for the glideslope and speed but it was less useful in the hover work and landing.
- BOSS required more interpretation and understanding; it also required a different control strategy than HDTS or visual flying.
- There was no spare capacity available when using BOSS; if the results were off, SA will break down, compounding the error.
- In the hover, there was too much information to scan and digest; it is difficult to interpret position, heading, and altitude at the same time.

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 U.S. Army. In evaluating four representative display technologies (a 3D conformal head-up display, audio presentation, map display, and tactile display) in operationally realistic situations, including departure and landing in both VMC and brownout, the 3D conformal HUD demonstrated an exceptionally strong effect on higher situation awareness, lower workload, better task performance, and higher preference by the pilots.[7] Furthermore, most recent data 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%.[8]

There are a number of limitations for the simulator and the in-flight study. An artificial situation was created for both studies that was more difficult than real life. In real life, as one approaches to land (before the "dust ball" could appear at 50 ft), pilots would use external visual references to execute the approach and set up their glide slope (unless there is a dark night when external visual references are not available). This is especially true during the flight trial when the subject pilots needed to pull the hood down. The blind flying hood was not an ideal method for the approach to landing phase toward DVE landing and contributed to disorientation in some pilots. With any flight trial, external factors (e.g., wind direction, traffic pattern, and noise restriction in the area) on the aircraft cannot be controlled and will affect trial conduct. The effectiveness of the helmet mounted HUD depends on proper implementation and interfacing of the symbology systems with the aircraft.

In conclusion: 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. The human visual system encompasses attentional mechanisms for selecting a small subset of possible stimuli for more extensive processing while relegating the rest to only limited analysis. Color, motion, orientation, or size attributes that define targets are supported as guiding attributes by a large amount of convincing data.[18] Our results further support motion, orientation, and size as important guiding attributes. The conformal 3D landing grid with virtual vertical reference towers, horizontal grid, and designated landing zone provide the necessary orientation cues to land the aircraft safely without external visual references. Specifically, the vertical reference 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 reacquisition of orientation cues (especially in lateral drift) when transitioning from VMC to IMC. The exact mechanism requires further laboratory investigation. An effective interface employed in legacy aircraft could negate the need for an expensive upgrade to heavily augmented digital flight control systems. Our simulator and in-flight study suggested that rapid prototyping of virtual world symbology is possible and can be tailored to the desired tasks. Future capabilities of 3D conformal symbology systems are limited only by our imagination.

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Authors and affiliations: Bob Cheung, Ph.D., M.Sc., DRDC Toronto Research Centre, Toronto, Ontario, Canada; Gregory Craig, Ph.D., amd Sion Jennings, B.ASc., National Research Council, Ottawa, Ontario, Canada; and Brad Steels, B.ASc., Robert Sceviour, B.ASc., Vaughn Cosman, B.Sc., and Peter Holst, B.Sc., Department of National Defense, Ottawa, Ontario, Canada.

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