# Helicopter Pilot Performance and Workload in a Following Task in a Degraded Visual Environment

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**BACKGROUND:** In this study, we investigated the impact of a loss of horizon due to atmospheric conditions on flight performance and workload of helicopter pilots during a low-altitude, dynamic flight task in windy conditions at sea. We also examined the potential benefits of a helmet-mounted display (HMD) for this specific task.

**METHODS:** In a fixed-based helicopter simulator, 16 military helicopter pilots were asked to follow a maneuvering go-fast vessel in a good visual environment (GVE) and in a degraded visual environment (DVE). DVE was simulated by fog, obscuring the horizon and reducing contrast. Both visual conditions were performed once with and once without an HMD, which was simulated by projecting head-slaved symbology in the outside visuals. Objective measures included flight performance, control inputs, gaze direction, and relative positioning. Subjective measures included self-ratings on performance, situation awareness, and workload.

**RESULTS:** The results showed that in DVE the pilots perceived higher workload and were flying closer to the go-fast vessel than in GVE. Consequently, they responded with larger control inputs to maneuvers of the vessel. The availability of an HMD hardly improved flight performance but did allow the pilots to focus their attention more outside, significantly improving their situation awareness and reducing workload. These benefits were found in DVE as well as GVE conditions.

**DISCUSSION:** DVE negatively affects workload and flight performance of helicopter pilots in a dynamic, low-altitude following task. An HMD can help improve situation awareness and lower the workload during such a task, irrespective of the visual conditions.

**KEYWORDS:** human factors, military aviation, helmet-mounted display, aerospace, situational awareness.

**Ledegang WD, van der Burg E, Valk PJL, Houben MMJ, Groen EL. *Helicopter pilot performance and workload in a following task in a degraded visual environment*. Aerosp Med Hum Perform. 2024; 95(1):16–24.**



Helicopter operations in a degraded visual environment (DVE) have been associated with an increased risk of spatial disorientation in military pilots.[11] When outside visual references are lost due to atmospheric conditions, such as fog, the pilot must rely on cockpit instruments to maintain spatial orientation. When executing a task that requires the pilot to look outside, such as a low-altitude following task, the attention shift between cockpit and outside visual may increase workload.

One such following task, regularly performed by helicopter pilots of the Royal Netherlands Air Force (RNLAF), is the interception of suspicious powerboats, or "go-fast" vessels. Already in good visibility, go-fast following involves high workload because it occurs at low altitude and the pilot needs to anticipate the (evasive) maneuvering of the go-fast vessel while making sure that the door-gunner has a clear line of sight to the vessel. Under windy circumstances the pilot should also take the wind direction and speed into account, especially when flying at low speed with high power settings, because a strong tailwind may increase the risk of entering a vortex ring state (VRS). VRS, also designated "settling with insufficient power", is an aerodynamic condition that results in a sudden loss of lift.

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This manuscript was received for review in March 2023. It was accepted for publication in November 2023.

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DOI: https://doi.org/10.3357/AMHP.6266.2024

Go-fast following may become even more challenging in foggy conditions because it is more difficult to estimate the helicopter's attitude relative to the horizon and its altitude above sea level. The primary goal of the current simulator study was to quantitatively assess the effects of DVE on flight performance and workload of helicopter pilots. We hypothesize that pilots experience higher workload and show degraded performance when performing a go-fast following task in DVE as compared to a good visual environment (GVE).

Existing literature has shown that the availability of a head-mounted display (HMD), which presents the essential flight parameters as an overlay to the pilots' field of view, can enhance situational awareness and mitigate increase of workload due to DVE (e.g., due to mist in navigation tasks or brownout effects in departure and landing).[2,4,13] To our knowledge, it is unclear whether an HMD also provides added value during a go-fast following task in DVE. Therefore, the secondary goal of the current simulator study was to investigate if an HMD can mitigate the effects of DVE during a go-fast following task. We hypothesize that an HMD can improve the pilot's flight performance in this task and decrease workload, especially in DVE.

## METHODS

### Subjects

There were 16 active-duty male RNLAF helicopter pilots who participated in this simulator study. Of those, eight (mean age = 39.3 yr, SEM = 2.9) were qualified NH90 helicopter pilots who accumulated an average of 1733 (SEM = 822) flight hours and 909 (SEM = 259) simulator hours. On average, they had flown 246 (SEM = 149) hours with an HMD (in other helicopters since currently no HMD is available in the RNLAF NH90). These pilots had experience with 29 (SEM = 18, ranging between 0–150) go-fast interceptions or so-called car-blocking operations (CBO), which is a following task over land with similar challenges in some respects. The other eight pilots (mean age = 34.6 yr, SEM = 1.8) were qualified AS-532U2 Cougar Mk.II helicopter pilots who accumulated 1213 (SEM = 223) flight hours, 259 (SEM = 44) simulator hours, 320 (SEM = 48) HMD hours, and 24 (SEM = 5, ranging between 0–50) go-fast interceptions or CBO tasks. Prior to the experiment, all pilots signed an informed consent document stating that the details of the experiment had been sufficiently explained and that they participated voluntarily. The experiment was conducted with approval of the institutional ethics committee and was in accordance with the (revised) Helsinki Declaration.

### Materials

A fixed-base generic helicopter cockpit mock-up was used, consisting of a vibrating seat, collective, cyclic and pedals, and a display with cockpit instruments. The mock-up was placed inside a projection dome (240° x 155° field of view) for presentation of outside imagery. The mock-up was turned 30° to the left relative to the dome to increase the field-of-view on the right-hand side of the pilot, where most of the visuals were shown to perform the task. See **Fig. 1** for an illustration of the experimental setup.

The flight model characteristics were comparable to Cougar and NH90 types of helicopters and were validated with test pilots from both platforms. The HMD, featuring a 30° field of view, was simulated by projecting head-slaved HMD-symbology as overlay in the out-the-window visual, driven by real-time tracking of the pilots' head direction. HMD-symbology was primarily based on the AH-64 Integrated Helmet and Display Sighting System, while AH-64-specific information was left out, and a First Limit Indication (engine torque information) and wind vector were added, based on the Cougar Advanced Night Vision System-Head Up Display layout. The final layout was verified and evaluated with two test pilots, who considered the layout adequate for this experiment. Cockpit mock-up and simulation software, including flight model, HMD-symbology, and synchronized logging were developed by multiSIM BV (Soesterberg, Netherlands).

### Procedure

Prior to the experimental conditions, each pilot was familiarized with the flight model, visual environment, and HMD, until they indicated that they felt proficient enough to be able to perform the tasks (as reflected by a rating above 7 out of 10). This typically took about 20–30 min. Subsequently, each pilot performed the go-fast following task in four different experimental conditions, between which two factors were manipulated in a 2×2 within-subjects design. The first factor involved the outside visibility, which was either a GVE or a DVE. The second factor comprised the availability of the HMD, which was varied between absent (cockpit instruments only) in the "No HMD" conditions and present (cockpit instruments and HMD) in the "HMD" conditions.

All conditions started with takeoff from a ship, navigation to the go-fast, and a hover in position next to and behind the go-fast vessel. When comfortable in hover, the pilot was

**Fig. 1.** Simulator setup of the generic helicopter cockpit inside a dome projection with head-slaved helmet-mounted display (HMD) projection.

instructed to maintain position and keep the go-fast vessel at a bearing between one and three o'clock (i.e., relative orientation between 30° and 90°). The takeoff and navigation to the go-fast were included to create a more realistic scenario, while only the following task was part of the test. In other words, the data collection was initiated when the go-fast vessel started maneuvering.

To create a high-workload scenario, the pilot was instructed to manually control the helicopter, i.e., without autopilot. Also, the task was performed in relatively strong wind conditions of about 25–30 kts (12.9–15.4 $m \cdot s^{-1}$) from the east. Four different, but similar, preprogrammed go-fast routes were defined. Besides some mild turns and speed changes, each scenario included two unexpected maneuvers of the go-fast vessel, which required the pilot to respond immediately while taking the wind direction into account. One unexpected go-fast maneuver consisted of a sharp turn toward the helicopter ending up in tailwind conditions, and the other event consisted of an abrupt deceleration to a standstill of the go-fast vessel in tailwind conditions. Each condition lasted about 7 min. To control for order effects, the conditions and go-fast routes were counterbalanced across the subjects according to a full Latin-square design.

For each condition, the following objective measures were computed based on logged data from the simulator and the head tracker, all sampled with 100 Hz: 1) control behavior (cyclic pitch and roll, pedal yaw and collective inputs); 2) flight performance (altitude, vertical velocity, airspeed, torque); 3) positioning with respect to the go-fast (relative heading, distance, and reactions to the go-fast standstill and when the go-fast performed a sharp turn); and 4) the pilot's head direction (number of instrument cross-checks, percentage of time spent looking outside versus at the cockpit instruments). For a Cougar-type helicopter, VRS may occur at an airspeed below 30 kts (15.4 $m \cdot s^{-1}$) and a descent rate of more than 1200 $ft \cdot min^{-1}$ (6.1 $m \cdot s^{-1}$).[1] Both Cougar and NH90 pilots were familiar with the phenomenon of VRS. Since VRS was not actually implemented in the simulator's aerodynamic model, we identified moments where there was an increased risk. As confirmed by the test pilots, it is considered a dangerous situation when flying with tailwind at relatively low altitude whenever the airspeed drops below 20 kts (10.3 $m \cdot s^{-1}$), the torque setting becomes less than 5% below the First Limit Indicator (FLI) amber band, and the rate of descent exceeds 300 $ft \cdot min^{-1}$ (1.5 $m \cdot s^{-1}$).

The objective measures were analyzed over a 30-s time window during three phases of each condition: a) Initial phase (after fade-in, during which the go-fast vessel made some mild turns and speed changes); b) Standstill (abrupt slowing down of go-fast vessel to standstill); and c) Sharp Turn (sharp inward turn of the go-fast vessel toward the helicopter).

The pilots were asked to fill in three questionnaires containing statements and questions. All statements could be answered with a rating between 0 ("fully disagree") and 100 ("fully agree"). The first questionnaire was administered directly after the familiarization to verify whether the pilots felt comfortable with the simulator set up. The questionnaire contained statements on: 1) the controllability of the helicopter; 2) realism of the outside visibility; 3) HMD-readability; 4) comfort using the HMD; and 5) understanding of the task. A second questionnaire was administered after each condition, containing statements on: 1) performance; 2) task execution; 3) motivation; 4) effort; 5) awareness of flight parameters; 6) effort to keep stable flight parameters; 7) awareness of position relative to the go-fast; and 8) anticipation of the go-fast maneuvering. This questionnaire also contained a question about how the pilots divided their attention between "Neat and safe flight execution" and "Go-fast interception", adding up to a maximum of 100% (not per se adding up to 100% when attention was given to other aspects as well). The third and final questionnaire was administered at the end of the experiment, containing statements on the realism of: 1) the simulated DVE; 2) the HMD; and 3) the scenario. This questionnaire also contained questions about: 1) the pilots' decisions and applied strategy in relation to DVE and HMD; 2) their distribution of attention when using the HMD; and 3) a ranking of the four conditions with respect to the perceived challenge.

### Statistical Analysis

For each objective and subjective measure, we conducted a repeated measures analysis of variance (ANOVA) with visual environment (GVE versus DVE) and HMD (No HMD versus HMD) as within-subject variables, with alpha level set to 0.05. As effects on performance measures were expected to vary across the different maneuvers, this ANOVA was performed separately for each phase (Initial, Standstill, and Sharp Turn).

## RESULTS

As there were no significant differences in objective and subjective measures between pilots from the two different helicopter platforms, data of all subjects were treated similarly. After the familiarization phase, the pilots rated the fidelity of the helicopter control with mean = 72, SEM = 3.8; the visibility of the outside visuals with mean = 74, SEM = 4.1; the readability of the HMD with mean = 82, SEM = 4.8; the comfort of using the HMD with mean = 85, SEM = 3.8; and the understanding of the task with mean = 96, SEM = 1.7.

**Fig. 2** is an example showing time histories of several flight parameters during one condition, where the Initial phase, Sharp Turn, and Standstill are indicated by the shaded areas. Crucial moments with a combination of low calibrated airspeed (dotted line in the CAS graph), high descent rate (thick parts of the line in the VVI graph), and high torque (thick parts of the line in the FLI graph) are indicated by black squares in the altitude panel to indicate a high level of risk. The horizontal shaded area in the relative bearing panel represents the desired positioning such that the go-fast is kept at a bearing between 30°–90°. At the top of the head orientation panel, small dots indicate a switch between looking outside and looking at the cockpit instruments, and vice versa.

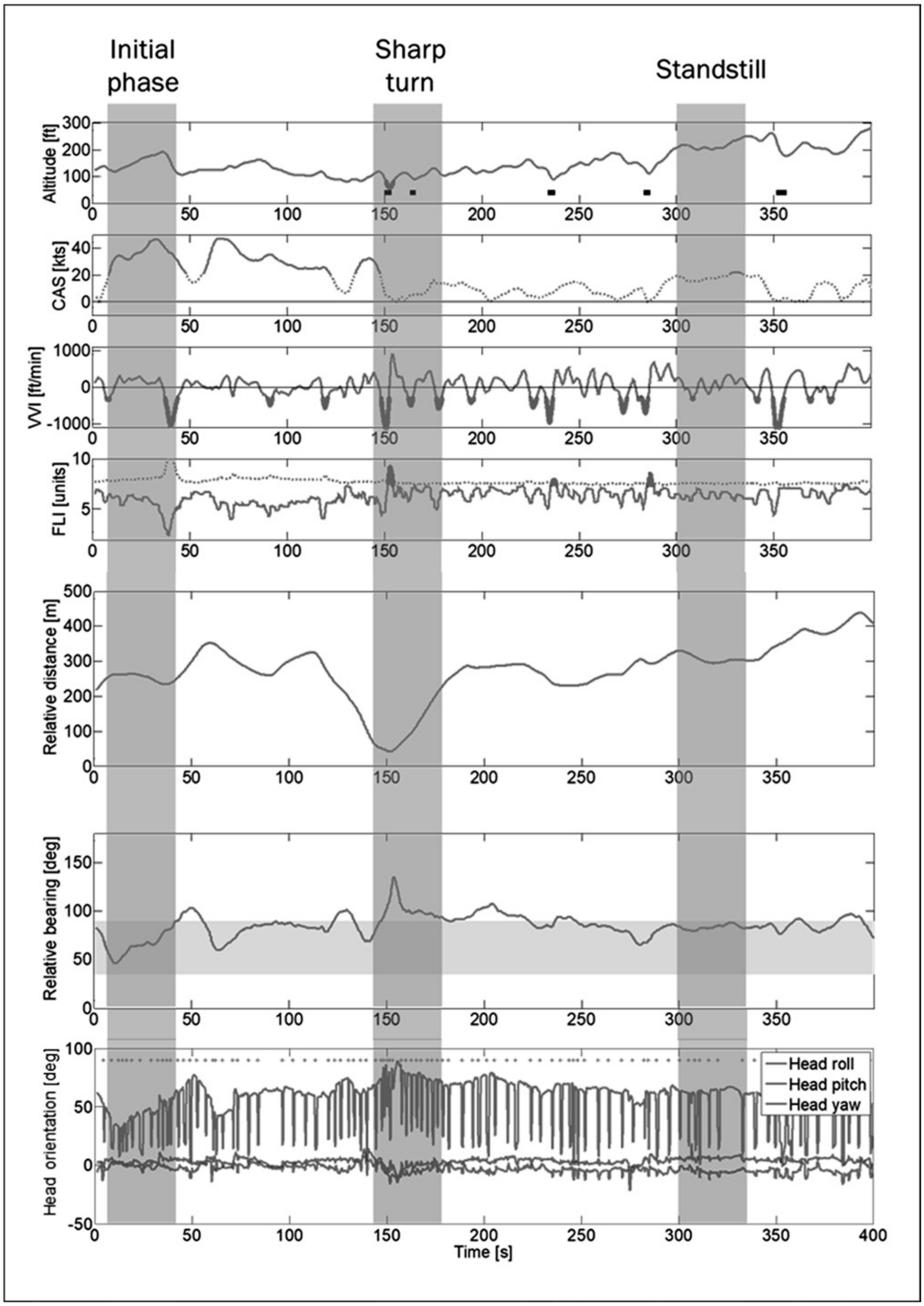


**Fig. 2.** Example run showing the Initial phase, Sharp Turn, and Standstill, in relation to time histories of flight performance in terms of altitude, calibrated airspeed (CAS), vertical velocity indicator (VVI), and torque (FLI), the helicopter positioning in terms of relative distance and relative bearing, and the head orientation of the pilot. Moments with low airspeed (dotted line in the CAS graph), high descent rate (thick parts of the line in the VVI graph), and high torque (thick parts of the line in the FLI graph) are marked by black squares in the altitude panel to indicate a high risk of entering a vortex ring state. The horizontal shaded area in the relative bearing panel represents the requested positioning such that the go-fast is kept at a bearing between 30°–90°. At the top of the head orientation panel, the dots indicate a jump between looking outside and looking at the cockpit instruments, and vice versa.

During the initial phase, the ANOVA yielded two significant visual environment × HMD interactions. The first interaction involved the standard deviation of altitude, $F(1, 15) = 4.6$, $P = 0.048$. In the GVE condition, there was slightly more variation in altitude when the pilots were using an HMD (3.8 m or 12.4 ft) compared to no HMD (2.3 m or 7.4 ft), $P < 0.002$. In the DVE condition, this HMD effect was not significant ($P = 0.529$). The second interaction involved the standard deviation of distance, $F(1, 15) = 6.9$, $P = 0.019$. In GVE, the variation of distance was smaller in HMD conditions (13.1 m or 43.0 ft) compared to No-HMD conditions (19.2 m or 63.0 ft). In DVE, we observed the opposite effect

**Table I.** Significant Main Effects of Visual Environment (GVE vs. DVE) and Helmet-Mounted Display (No HMD vs. HMD) for Objective Performance Measures During the Initial Phase.

| | INITIAL PHASE | | STATISTICS | | |
|---|---|---|---|---|---|
| PERFORMANCE MEASURE | GVE MEAN (SEM) | DVE MEAN (SEM) | *F* | *df* | *P* |
| Distance to go-fast (ft) | 780.8 (77.4) | 651.2 (53.1) | 9.0 | 1,15 | 0.009 |
| SD altitude (ft) | 8.9 (1.2) | 12.0 (1.8) | 5.0 | 1,15 | 0.04 |
| SD pitch angle (°) | 2.2 (0.2) | 2.6 (0.5) | 41.7 | 1,15 | <0.001 |
| SD vertical speed (ft · min$^{-1}$) | 111.4 (12.0) | 170.8 (23.4) | 14.7 | 1,15 | 0.002 |
| SD torque (%) | 3.6 (0.4) | 6.3 (0.7) | 26.3 | 1,15 | <0.001 |
| Max pitch angle (°) | 5.7 (0.6) | 11.4 (1.3) | 35.3 | 1,15 | <0.001 |
| Min pitch angle (°) | −5.8 (0.8) | −3.1 (0.5) | 16.0 | 1,15 | 0.001 |
| Max vertical speed (ft · min$^{-1}$) | 205.6 (26.9) | 306.6 (40.8) | 6.8 | 1,15 | 0.02 |
| Min vertical speed (ft · min$^{-1}$) | −217.9 (28.4) | −350.5 (54.4) | 17.8 | 1,15 | <0.001 |
| Max torque (%) | 53.5 (0.7) | 56.7 (1.2) | 7.3 | 1,15 | 0.02 |
| Min torque (%) | 40.3 (1.3) | 33.6 (1.9) | 24.6 | 1,15 | <0.001 |
| | NO HMD MEAN (SEM) | HMD MEAN (SEM) | | | |
| Cross-check rate (Hz) | 0.18 (0.026) | 0.047 (0.017) | 41.9 | 1,15 | <0.001 |

SEM = standard error of the mean; GVE = good visual environment; DVE = degraded visual environment.

(HMD = 17.1 m or 56.1 ft; No HMD = 12.8 m or 42.0 ft). There was no main effect for HMD regarding the standard deviation of distance ($P \geq 0.138$).

In addition to these interactions, for several objective performance measures visual environment and HMD showed a main effect during the Initial phase, as shown in **Table I**. On average, the pilots were flying significantly closer to the go-fast and with larger variations in altitude, pitch angle, vertical speed, and torque in DVE as compared to GVE. Also, the maximum and minimum values of pitch, vertical speed, and torque were significantly higher in DVE as compared to GVE. Regardless of the visual environment, the presence of the HMD resulted in less cross-checks of the cockpit instruments, as reflected by a lower cross-check rate (0.047 Hz) with an HMD as compared to the runs without an HMD (0.18 Hz).

During the Standstill phase of the go-fast vessel, the ANOVA yielded a significant two-way interaction between visual environment and HMD for the mean bearing, $F(1, 15) = 8.7$, $P = 0.001$. This means that in GVE the mean bearing was significantly different in HMD conditions (58.0°) versus No-HMD conditions (60.1°). In DVE, we observed the opposite pattern (HMD = 61.0 °, No HMD = 56.4°).

As shown in **Table II**, visual environment produced a main effect for several flight parameters in the Standstill phase. On average, the pilots responded with a higher pitch-up angle, ending up at a lower altitude, and at a smaller distance to the go-fast vessel in DVE as compared to GVE. The latter is also reflected by the difference in the maximum and minimum distance. Furthermore, variations in pitch attitude and in vertical speed were significantly larger in DVE compared to GVE. Correspondingly, the minimum pitch angle and minimum altitude achieved were lower in DVE than in GVE. The higher maximum climbing speed in DVE may be a compensatory response to the lower minimum

**Table II.** Significant Main Effects of Visual Environment (GVE vs. DVE) and Helmet-Mounted Display (No HMD vs. HMD) for Objective Performance Measures During the Go-Fast Standstill Phase.

| | STANDSTILL PHASE | | STATISTICS | | |
|---|---|---|---|---|---|
| PERFORMANCE MEASURE | GVE MEAN (SEM) | DVE MEAN (SEM) | *F* | *df* | *P* |
| Max pitch angle (°) | 11.5 (1.2) | 15.5 (1.4) | 13.7 | 1,15 | 0.002 |
| Min altitude (ft) | 97.3 (8.0) | 84.2 (6.9) | 5.8 | 1,15 | 0.03 |
| Distance to go-fast (ft) | 732.6 (72.2) | 662.4 (59.1) | 6.1 | 1,15 | 0.03 |
| Max distance to go-fast (ft) | 922.6 (83.3) | 826.4 (67.9) | 6.4 | 1,15 | 0.02 |
| Min distance to go-fast (ft) | 597.8 (65.9) | 516.7 (52.5) | 7.5 | 1,15 | 0.02 |
| SD pitch angle (°) | 3.9 (0.39) | 4.8 (0.47) | 11.6 | 1,15 | 0.004 |
| SD vertical speed (ft · min$^{-1}$) | 160.0 (13.1) | 217.3 (24.9) | 16.9 | 1,15 | <0.001 |
| Min pitch angle (°) | −8.7 (1.4) | −10.7 (1.6) | 11.8 | 1,15 | 0.004 |
| Max vertical speed (ft · min$^{-1}$) | 377.2 (31.6) | 463.9 (44.8) | 5.8 | 1,15 | 0.03 |
| Max torque (%) | 71.8 (2.5) | 78.0 (3.2) | 8.6 | 1,15 | 0.01 |
| Duration torque amber band | 0.15 (0.11) | 0.90 (0.34) | 9.0 | 1,15 | <0.001 |
| Min vertical speed (ft · min$^{-1}$) | −413.0 (48.4) | −603.8 (88.3) | 7.5 | 1,15 | 0.02 |
| | NO HMD MEAN (SEM) | HMD MEAN (SEM) | | | |
| Cross-check rate (Hz) | 0.24 (0.026) | 0.028 (0.010) | 71.0 | 1,15 | <0.001 |

SEM = standard error of the mean; GVE = good visual environment; DVE = degraded visual environment.

altitude. Furthermore, compared to GVE, the pilots responded to the sudden standstill with a significantly higher risk in DVE, indicated by the higher descent rate and higher torque settings that remained in the amber-band torque region for a longer duration. Regarding the main effect produced by the HMD, there was a significantly lower cross-check rate (0.028 Hz) with an HMD as compared to No HMD (0.24 Hz). This effect of HMD was not dependent on the visual environment since the visual environment x HMD interaction failed to reach significance.

We observed that there were different ways to respond to the sudden standstill of the go-fast vessel. In 70.3% of all trials, the pilots responded with a deceleration to keep in position left of the go-fast vessel. Other responses consisted of a hover into the wind direction at the front of the go-fast (18.8%), flying around the go-fast (6.3%), or hovering perpendicular to the wind direction next to the go-fast (4.7%).

For the Sharp Turn phase, the ANOVA yielded no significant two-way interactions for the objective performance measures. However, as listed in **Table III**, several significant main effects were found for visual environment and HMD. Similar to the Standstill phase, in DVE, the pilots were flying at a smaller distance to the go-fast as compared to GVE, ending up closer to the go-fast vessel. The response to the go-fast vessels' sharp turn was performed at a lower altitude in DVE as compared to GVE. Furthermore, in DVE the pilots responded to the sharp turn with a higher pitch angle in combination with a higher climb rate than in GVE. Regarding the parameters that contribute to the VRS risk, only the mean torque setting was significantly higher in DVE as compared to GVE. No significant difference was observed for descent rate. With the HMD, pilots could better (that is, more often) maintain adequate bearing relative to the go-fast vessel during the sharp turn as compared to No HMD (84.7 versus 77.6%). Also, with an HMD, pilots performed less cross-checks of the cockpit instruments (0.037 Hz with HMD as compared to 0.15 Hz in No-HMD conditions).

We observed different responses to the sharp inward turn of the go-fast vessel. In 48.4% of all recordings, the helicopter pilot responded with a relatively tight 270° turn to maintain vision on the go-fast. Other responses involved a quick-stop to turn with the go-fast (25.0%), a 270° turn without maintaining vision on the go-fast (14.1%), and other variants of these strategies (12.5%).

All pilots indicated that they were highly motivated to perform the task (overall motivation was approximately 95%), independent of the HMD and visual environment conditions, as the ANOVA did not show significant differences for these aspects. This indicates that the motivation was in general high and not dependent on the conditions.

The ANOVA showed no significant interaction effects between the visual environment and HMD presence for any of the subjective measures. However, both factors did produce several main effects as listed in **Table IV**, which presents the mean (and SEM) values of subjective ratings for DVE and GVE (averaged over No HMD and HMD) in the upper half of the table, while the lower half of the table shows the values for the No-HMD and HMD conditions (averaged over DVE and GVE), respectively.

On average, the pilots rated their Performance and Task Execution significantly lower in DVE than in GVE. In addition, the mean Effort rating was higher in DVE than in GVE, which is also true for the Effort to keep parameters stable. Also, the mean rating for Anticipation was significantly lower in DVE as compared to GVE.

The presence of the HMD significantly improved the ratings for Task Execution compared to the absence of the HMD. Also, the HMD provided better awareness of the flight parameters, and better rating for maintaining stable parameters. Due to the presence of the HMD, the average workload rating was reduced. The presence of the HMD also resulted in higher ratings for Anticipation of the maneuvering of the go-fast vessel.

The pilots judged the condition in GVE with HMD as the easiest [1.44, on a scale from 1 ("easiest") to 4 ("most difficult")]. The GVE without HMD and DVE with HMD were perceived as being equally difficult (2.31 and 2.63, respectively), whereas the DVE without HMD was judged as most difficult (3.63).

With respect to the allocation of attention, in GVE, the pilots allocated 58.4 ± 3.3% of their attention to the outside visuals, 34.7 ± 2.9% to the HMD, and 5.9 ± 1.1% to the cockpit

**Table III.** Significant Main Effects of Visual Environment (GVE vs. DVE) and Helmet-Mounted Display (No HMD vs. HMD) for Objective Performance Measures During the Go-Fast Sharp Turn Phase.

| | SHARP TURN PHASE | | STATISTICS | | |
|---|---|---|---|---|---|
| **PERFORMANCE MEASURE** | **GVE MEAN (SEM)** | **DVE MEAN (SEM)** | ***F*** | ***df*** | ***P*** |
| Mean distance (ft) | 731.0 (78.4) | 537.7 (39.4) | 11.7 | 1,15 | 0.004 |
| Min distance (ft) | 354.3 (52.2) | 205.7 (34.4) | 13.5 | 1,15 | 0.002 |
| Min altitude (ft) | 93.3 (7.7) | 72.3 (5.6) | 12.3 | 1,15 | 0.003 |
| Max pitch (°) | 13.5 (1.7) | 16.2 (1.7) | 5.0 | 1,15 | 0.04 |
| Max climb rate (ft · min$^{-1}$) | 482.5 (52.8) | 598.1 (68.3) | 8.0 | 1,15 | 0.01 |
| Max torque (%) | 64.9 (2.5) | 72.3 (2.7) | 19.6 | 1,15 | <0.001 |
| | **NO HMD MEAN (SEM)** | **HMD MEAN (SEM)** | | | |
| Adequate bearing (%) | 77.6 (5.6) | 84.7 (3.8) | 5.5 | 1,15 | 0.03 |
| Cross-check rate (Hz) | 0.15 (0.014) | 0.037 (0.011) | 73.7 | 1,15 | <0.001 |

SEM = standard error of the mean; GVE = good visual environment; DVE = degraded visual environment.

**Table IV.** Statistical Analyses for the Subjective Measures.

| | SUBJECTIVE RESULTS | | STATISTICS | | |
|---|---|---|---|---|---|
| SUBJECTIVE MEASURE† | GVE MEAN (SEM) | DVE MEAN (SEM) | *F* | *df* | *P* |
| Performance | 75.3 (4.0) | 62.3 (4.7) | 8.34 | 1,15 | 0.011* |
| Task execution | 86.7 (3.1) | 77.2 (4.3) | 9.52 | 1,15 | 0.008* |
| Motivation | 95.1 (1.6) | 93.9 (2.4) | 0.66 | 1,15 | 0.430 |
| Overall effort | 54.2 (5.5) | 68.8 (5.3) | 7.15 | 1,15 | 0.017* |
| Aware of flight parameters | 72.2 (4.8) | 71.1 (4.1) | 0.09 | 1,15 | 0.763 |
| Workload flying‡ | 46.7 (4.5) | 53.3 (4.0) | 3.85 | 1,15 | 0.069 |
| Workload following‡ | 52.7 (4.6) | 46.3 (4.1) | 3.50 | 1,15 | 0.081 |
| Effort stable parameters | 39.0 (6.3) | 55.2 (5.2) | 6.22 | 1,15 | 0.025* |
| Awareness positioning | 85.9 (4.6) | 87.3 (3.8) | 0.38 | 1,15 | 0.548 |
| Anticipation | 80.4 (3.7) | 68.2 (5.1) | 12.26 | 1,15 | 0.003* |
| | NO HMD MEAN (SEM) | HMD MEAN (SEM) | | | |
| Performance | 65.2 (4.6) | 72.4 (4.1) | 3.86 | 1,15 | 0.068 |
| Task execution | 78.4 (4.3) | 85.5 (3.2) | 5.71 | 1,15 | 0.030* |
| Motivation | 94.2 (2.0) | 94.8 (1.9) | 0.41 | 1,15 | 0.531 |
| Overall effort | 64.5 (5.3) | 58.5 (5.4) | 3.13 | 1,15 | 0.097 |
| Aware of flight parameters | 64.9 (4.6) | 78.4 (4.3) | 16.75 | 1,15 | 0.001* |
| Workload flying‡ | 54.1 (4.2) | 45.9 (4.3) | 10.61 | 1,15 | 0.005* |
| Workload following‡ | 45.3 (4.3) | 53.6 (4.3) | 11.00 | 1,15 | 0.005* |
| Effort stable parameters | 54.4 (5.5) | 39.8 (6.0) | 8.49 | 1,15 | 0.011* |
| Awareness positioning | 82.7 (5.0) | 90.5 (3.3) | 4.34 | 1,15 | 0.055 |
| Anticipation | 69.7 (5.1) | 78.9 (3.8) | 6.41 | 1,15 | 0.023* |

Note that the ANOVA yielded no significant two-way interactions for any combination of subjective measures. †0 disagree–100 agree; *significant at $P < 0.05$; ‡Note that "workload flying" and "workload following" are dependent on each other since they added up to ≤100, representing the dominant factors of the total workload. SEM = standard error of the mean; GVE = good visual environment; DVE = degraded visual environment.

instruments. In DVE, they gave most of their attention to the HMD (48.8 ± 4.3%) and outside visuals (42.5 ± 4.5%), followed by the cockpit instruments (8.4 ± 1.9%).

## DISCUSSION

The results of this study confirm that the helicopter go-fast following task was significantly more difficult to perform in DVE than in GVE, as indicated by both the subjective ratings and objective measures in all three phases (Initial phase, Standstill, and Sharp Turn). According to the objective results, the pilots flew closer to the go-fast vessel in DVE compared to GVE. In the Initial phase (i.e., prior to the more dynamic maneuvers of the go-fast vessel), the difference was 17%, and in the Standstill and Sharp Turn phases, the difference amounted to 10% and 26%, respectively. In DVE, the visual contrast was lower than in GVE, so we assume that the pilots were flying closer to the vessel, trying to maintain adequate visibility on the go-fast vessel. However, flying at a shorter distance from the go-fast vessel reduces the margin to anticipate its maneuvering. This may explain why, in DVE, the pilots responded with higher pitch angle to decelerate the helicopter. Furthermore, higher vertical speeds were observed in DVE than in GVE during the Standstill (23% higher) and Sharp Turn (24% higher). Especially during the Standstill, the flight parameters related to VRS showed a higher risk in DVE than in GVE. In 9 out of 64 recordings, the descent rate exceeded 1200 $ft \cdot min^{-1}$ (6.1 $m \cdot s^{-1}$), up to 1995 $ft \cdot min^{-1}$ (10.1 $m \cdot s^{-1}$), which can be considered unsafe at the low altitude at which the task was being performed. As most of these events were found in DVE, these findings suggest that the loss of a horizon due to atmospheric conditions makes it more difficult for pilots to remain aware of the helicopter attitude in relation to the wind direction, as well as to anticipate an imminent VRS. According to the subjective ratings on workload and situational awareness (SA), the execution of the go-fast following task was 9% more difficult in DVE, requiring 27% more overall effort and 42% more effort to keep stable flight parameters, as compared to GVE. Anticipating the go-fast maneuvering was perceived as 15% more difficult in DVE compared to GVE. Together, these results show that DVE has negative effects on the pilots' flight performance and workload during a go-fast following task.

Regarding the added value of an HMD, the pilots rated their task execution 9% better in conditions with HMD, while putting in 27% less effort to keep stable parameters, as compared to conditions without HMD. The presence of an HMD allowed 18% more attention for the go-fast following task instead of giving attention to the flight execution compared to conditions without HMD. Furthermore, pilots indicated that the HMD improved their SA up to 21%, as reflected by higher ratings on the awareness of flight parameters and the ability to anticipate go-fast maneuverings. These findings are likely related to the fact that the flight parameters were presented in the pilot's primary field of view, reducing the need to regularly cross-check the cockpit instruments. Indeed, with an HMD the pilots performed a cross-check about once every 30 s, while they checked their instruments about once every 5 s when there was no HMD available. This confirms a well-known benefit of superimposed symbology, i.e., that it allows pilots to check the flight parameters continuously while maintaining their attention on the outside visual environment.[3,6,14] During the go-fast sharp turn, the pilots were 9% better able to maintain an adequate bearing to the go-fast when they used an HMD. Apart from the standard deviations in altitude and distance during the Initial phase, and the mean bearing during the Standstill phase, there were hardly any significant interaction effects between the visual environment and the presence of the HMD. Irrespective of the visual environment, the availability of an HMD had positive effects on the execution of the task, workload, and SA. This means that an HMD showed added value for executing a go-fast following task in both GVE and DVE conditions.

Whereas existing literature mainly covers the added value of an HMD in rotorcraft-induced DVE, such as (brownout) departure and landings, and during navigational tasks in reduced visibility, we focused on a highly dynamic following task at low altitude. Despite this very different task, our findings seem in line with existing literature on the added value of an HMD in DVE conditions. Therefore, we expect that the results we found in this study also apply to other helicopter scenarios with high workload and dynamic flying in low-visibility conditions. This includes, for example, low-level flying while avoiding obstacles and CBO.

There are several limitations to this study. First, the simulator was fixed-base, thus vestibular feedback on helicopter maneuvers (other than produced by the vibrating chair) were lacking. Second, a generic helicopter flight model was used, which, although validated by Cougar and NH90 helicopter pilots, did not respond exactly in the same way as a real helicopter. Third, the HMD was simulated by head-slaved projection of symbology in the out-the-window visual. Although this was rated as very realistic, a real HMD integrated in the simulator environment would improve the realism. Furthermore, from literature it is known that an HMD can potentially induce clutter that may occlude objects in the outside scene,[15] attract attention both perceptually and attentionally,[9,10] create reading problems in large contrast differences,[5] and can lead to reduced peripheral vision due to the HMD structure.[12] However, in our study none of these downside aspects were mentioned by the pilots, which may be related to the visually empty environment at sea, the lighting conditions of the simulator environment, and the projection of HMD symbology in the outside visuals. In addition, prolonged use of an HMD can induce eye strain and motion sickness.[7,8] Again, none of these aspects were observed, which may be related to the limited exposure time in our study. Fourth, some of the participating pilots had limited experience with a go-fast following task and had limited time to get familiar with this task and the use of the simulated HMD. It can be expected that the benefits of an HMD become more pronounced when pilots are fully trained to operate with such a device. Fifth, because the subjects knew that they were in a simulated environment with no real risk, they may have adapted their behavior and strategy to this unnaturally forgiving environment. However, given a very high overall motivation of approximately 95%, it is likely that they tried to perform the task as they would in real life.

In conclusion, the results of this simulator study show that helicopter pilots have more difficulty in performing a high-workload following task in DVE as compared to GVE. The availability of an HMD, which projects flight-relevant symbology onto the pilot's field of view, improved the ability to keep an adequate bearing with respect to the go-fast, and allowed the pilots to focus their attention more outside, significantly improving SA and reducing workload. These benefits were found in both DVE and GVE conditions, indicating that an HMD is of added value to helicopter pilots when performing a following task irrespective of the visual environment. Together, these results suggest that the availability of an HMD for helicopter pilots may enhance mission success when performing a go-fast following task.

## ACKNOWLEDGMENTS

This research is supported by the Defence Research and Development Programme V1917 "5thGenStressors" and is a cooperation between TNO and the Royal Netherlands Air Force aeromedical institute Centre for Man and Aviation. We thank all RNLAF pilots for their enthusiastic participation. We wish to acknowledge all RNLAF subject matter experts that were involved in the preparation of the experiment and interpretation of the results. Finally, we thank multiSIM BV for their support and development of the simulator environment.

*Financial Disclosure Statement:* The authors have no competing interests to declare.

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