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Research Project EASA.2011.02

Helicopter Flight in a Degraded Visual Environment

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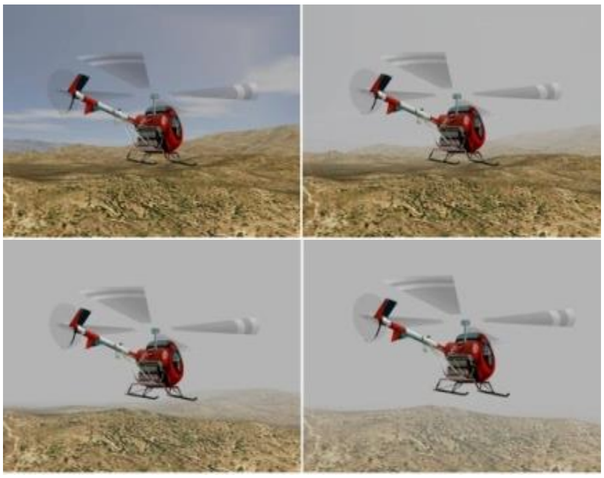
EXECUTIVE SUMMARY

Helicopter Flight in a Degraded Visual Environment

Final report



Problem area

Quite a number of rotorcraft accidents occurred due to a degraded visual cueing environment the pilot got into. The group of rotorcraft and pilots most frequently involved seemed to be the light, single-engined piston-powered rotorcraft with a relatively inexperienced pilot.

Description of work

After a tender procedure by EASA, NLR was given the contract to investigate new means of providing additional visual and aural cueing in the rotorcraft cockpit to aid the pilot in recovering from the degraded situation to a safe flight condition.

Three visual enhancement concepts and one audio concept were implemented and tested using NLR's Helicopter Pilot Station. These were the Malcolm Horizon, the HUD Orange Peel and the LED concept, while for the audio concept a Helicopter Terrain Awareness and Warning System was implemented using the Time-To-Impact as a warning threshold.

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Results and conclusions

The Malcolm Horizon and HUD Orange Peel were well accepted by the pilots, but the LED concept, based hypothetically on the working of peripheral cueing, was neutrally accepted or even (fully) rejected.

With the Malcolm Horizon and HUD Orange Peel some additional features are needed to improve their functioning. The HTAWS concept worked well, even though one case of a missed alert by the system occurred, which immediately led to a crash.

The eye tracker data showed that pilots obviously looked at the outside display of the various visual concepts, except with the LED concept, where they spent looking at the instrument panel even more than with no concept. With the CFIT scenario the HUD Orange Peel drew attention away from the wide outside scanning, which could be detrimental to safety.

It is recommended to further test the HUD Orange peel, the Malcolm Horizon and the LED concept as a means to recover from unusual attitude, and with the present artificial horizon removed from the cockpit in order to fully evaluate the visual enhancement brought about by the concepts. Also further development work is recommended for the LED concept to increase the present technology readiness level from 3-4 to 6 or 7 through further design and manned simulations. With these manned simulations it is recommended to use also (curved) cockpit windows as much as possible, which these concepts (except the LED) make use of for reflection of the imagery.

Applicability

The Malcolm Horizon or HUD Orange Peel and an upgraded LED concept can be used advantageously to aid a pilot in getting away safely from an inadvertent entry into IMC conditions, a condition that contributed most to the occurrence of accidents among small helicopters with relatively inexperienced pilots. The HUD Orange Peel and the HTAWS can be used advantageously to avoid ground contact in a situation of reduced ground cues, provided no missed alerts occur with the HTAWS.

Helicopter Flight in a Degraded Visual Environment

Final report

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Customer

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Summary

Quite a number of rotorcraft accidents occurred due to a degraded visual cueing environment the pilot got into. The group of rotorcraft and pilots most frequently involved seemed to be the light, single-engined piston-powered rotorcraft with a relatively inexperienced pilot. Most dangerous conditions were found to be inadvertent entry into IMC and controlled flight into terrain.

After a tender procedure by EASA, NLR was given the contract to investigate new means of providing additional visual and aural cueing in the rotorcraft cockpit to aid the pilot in recovering from the degraded situation to a safe flight condition.

Three visual enhancement concepts and one audio concept were engineered, implemented and tested using NLR's Helicopter Pilot Station. These were the Malcolm Horizon (MH), the HUD Orange Peel (HOP) and the LED concept (LED), while for the audio concept a Helicopter Terrain Awareness and Warning System (HTAWS) was implemented using the Time-To-Impact as a warning threshold.

The Malcolm Horizon and HUD Orange Peel were well accepted by the pilots, but the LED concept, based hypothetically on the working of peripheral cueing, was neutrally accepted or even (fully) rejected. This is not surprising since the technological readiness level of this concept is quite low (TRL~3), much lower than that for the MH (TRL=7) or the HOP (TRL=4 for the HOP with the red ground bar; TRL=6 for the HOP without the ground bar). Additional development is therefore needed to improve the peripheral cueing aspects of the LED concept, for example by using up-left/down-right moving light cues to indicate roll angle (as well as pitch angle) and additional simulations to increase the TRL to the medium readiness level (TRL=4-6).

With the MH and HOP some additional features are needed to improve their functioning; these have mostly to do with providing for a reference indication, as suggested by the experimental test pilot from EASA. For the MH the line itself needs to be extended or modified as in case of a bank angle of more than 90° the roll attitude indication will become ambiguous. The HTAWS concept worked well, even though one case of a system missed alert occurred, which immediately led to a crash.

In terms of the Visual Usable Cue Environment (UCE), dependent upon the Visual Cue Ratings (VCR) given by the pilots, the LED concept hardly improved the UCE compared to the baseline ('no concept'). The MH gave a significant improvement in UCE by mostly improving the attitude cues, improving the UCE from near the UCE=3 boundary to mid-range between UCE=1 and UCE=3. The HOP further improved the UCE to near UCE=1 by mostly improving the translational cueing, owing to the presence of a height indication bar.

The MH or HOP can be used advantageously to aid a pilot in getting away safely from an inadvertent entry into IMC conditions, a condition that contributed most to the occurrence of accidents among small helicopters with relatively inexperienced pilots. The HOP and/or the HTAWS can be used advantageously to avoid ground contact in a situation of reduced ground cues in situations where there is a risk of Controlled Flight Into Terrain (CFIT), provided no missed alerts occur with the HTAWS.

The eye tracker data showed to no surprise that pilots spent more attention outside to where the symbology was presented, i.e. locally in front of the pilot for the HOP, or in a wider scan for the Malcolm Horizon. With the LED concept, however, hardly any time was spent looking outside, and even more focus was given on the instrument panel than with no concept. It is unclear why this happened. With the CFIT scenario the data showed that the HOP drew attention away from the overall outside scan. Although safety and situational awareness were rated to be better with the HOP than without a concept, drawing away attention in this scenario could be detrimental to safety, certainly if more aircraft would be involved. With the HTAWS pilots spent 20% more time watching the instruments than with no concept, at the expense of scanning widely outside. Apparently the HTAWS system was a strong confidence builder that could alleviate the pilot from the task of searching for obstacles. As such the use of the eye tracker in this project was very valuable in assessing the actual use of the visual (and also audio) use of the various enhancement concepts.

It is recommended to further test the visual enhancement concepts as a means to recover from unusual attitudes, and with the present artificial horizon removed from the cockpit in order to fully evaluate the visual enhancement brought about by the concepts. Also a further improvement in the LED concept is recommended to be made and tested. As a next step up the Technology Readiness ladder it is recommended to perform any next series of manned simulations using (curved) cockpit windows except for the LED concept (where they aren't needed), scaled to size, for reflecting the lights, lines, etc. that the concepts are based upon.

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Content

Abbreviations

Acronym	Description
ADI	Attitude Director Indicator
AHRS	Attitude and Heading Reference System
CFIT	Controlled Flight Into Terrain
DVE	Degraded Visual Environment
EASA	European Aviation Safety Agency
EHSAT	European Helicopter Safety Analysis Team
FOV	Field-Of-View
FR	Flight Risk
GA	General Aviation
GPS	Global Positioning System
GPWS	Ground Proximity Warning System
HDVE	Helicopter Degraded Visual Environment
HFACS	Human Factors Analysis and Classification System
HOP	HUD Orange Peel
HPS	Helicopter Pilot Station
h_R	Radio height
HTAWS	Helicopter Terrain Awareness Warning System
HUD	Head-Up Display
IAS	Indicated Air Speed
IFR	Instrument Flight Rules
IIMC	Inadvertent entry Into IMC
IMC	Instrument Meteorological Conditions
IR	Instrument Rating
LED	Light-Emitting Diode
MH	Malcolm Horizon
MTOW	Maximum Take-Off Weight
NLR	National Aerospace Laboratory NLR
ROD	Rate Of Descent
SD	Spatial Disorientation
SPS	Standard Problem Statement
UCE	Useable Cue Environment
VCR	Visual Cue Rating
VFR	Visual Flight Rules

VMC	**Visual Meteorological Conditions**
φ	**Roll angle**
θ	**Pitch angle**

1 Introduction and background

Helicopter flights are particularly exposed to safety hazards when exposed to conditions associated with a “Degraded Visual Environment” (DVE). Looking at the rotorcraft accident statistics, this issue played for quite a while within the member states of the European Aviation Safety Agency (EASA). Therefore EASA has requested the National Aerospace Laboratory (NLR), through a tender, to perform a project called ‘Helicopter flight in Degraded Visual Environment (HDVE)’. The subject of this HDVE project is the provision of a study on unintended helicopter flight into a degraded visual environment during VFR (Visual Flight Rules) operations, aiming at investigating the feasibility and effectiveness of a number of aids for pilots to enhance the visual and/or audio cueing and situational awareness (e.g. attitude, terrain proximity) to mitigate the safety hazards associated with DVE.

Prior to this request the UK’s Civil Aviation Agency (CAA) already performed basic research on this reduced visual cueing in order to be able to quantify when a degraded visual condition can be classified as such, and what the interaction is between these conditions and the aircraft flight characteristics.

A big issue of course with a degraded visual environment is the safety hazard involved. From safety records it turned out that the highest frequency of occurrence of accidents with helicopters was with the small types (Robinson R44 like), and for a few special conditions.

Upon request from EASA, NLR held a brainstorm session both internally and with EASA officials about a number of visual enhancement concepts that might be eligible for evaluation. It resulted in a list of 4 enhancement concepts, 3 visual enhancement concepts and one audio enhancement concept, which will be further detailed in section 4.5. These are the Malcolm Horizon (MH), the HUD Orange Peel (HOP), the LED concept (LED) and the Helicopter Terrain Awareness and Warning System (HTAWS). They must be understood to be basic, simple systems fit to be mounted in a small helicopter.

This report is the HDVE Study’s Final Report. A literature review on the visual enhancement concepts was performed in chapter 2. A human-in-the-loop evaluation on a flight simulator was performed and reported on in chapters 3 to 6. The report also provides recommendations for the way forward (chapters 7 to 8).

2 Literature review

2.1 CAA report

Preliminary work in the area of visual cueing was performed by the CAA (Ref. [10]), who evaluated basic aspects of visual cueing and the guidance process the pilots adopts in order to perform his flying task. The Visual Cue Ratings as used in the military helicopter handling qualities specification document, the ADS33-E (Ref. [8]), were considered and various scenarios developed in order to study the interaction between handling qualities and required visual cues.

2.2 Malcolm Horizon reports

Spatial Disorientation (SD) is a constant contributing factor to the rate of fatal aviation accidents. SD occurs as a result of perceptual errors that can be attributed in part to the inefficient presentation of synthetic orientation cues via the attitude indicator when external visual conditions are poor. Improvements in the design of the attitude indicator may help to eliminate instrumentation as a factor in the onset of SD. In Ref. [10] one of the concepts evaluated was a concept known as an extended horizon line or Malcolm Horizon (MH), more fully described in §4.5.1. A clear and significant improvement in attitude task performance was found with the addition of the extended horizon line. The MH seemed to equalize attitude performance across various display sizes, even for a central or foveal display as small as three inches in width.
The history and the future of the Malcolm Horizon (MH) has been described by Malcolm (Ref. [3]). The theory of peripheral vision has been described by Money in Ref. [2], explaining why it is important to have this peripheral or ambient vision, used. In Ref. [4] Gillingham describes an evaluation done on the Malcolm Horizon in a moving base simulator, and a review of the peripheral vision horizon display was given by Hameluck & Stager (Ref. [6]). All of these applications are for fixed-wing aircraft. No rotary-wing application has yet been found.

2.3 HUD orange peel reports

Cone and Hassoun (Ref. [5]) investigated a set of attitude awareness enhancements for potential incorporation into the F-16 aircraft, among which were both a small and a large orange peel concept. The small orange peel was referenced to the flight path vector/marker, while the large orange peel was fixed in position on the HUD. Fifteen pilots flew a series of unusual attitude recoveries and mission demonstration tasks during which reaction time, error rate, and subjective ratings were collected, Results showed faster reaction times, especially in nose-down conditions, and strong subjective preference for the modified HUD format, However, the opinions about the orange peel were rather mixed. The large orange peel was preferred as the small one moved with the flight path marker over the HUD field of view, and could therefore move quite considerably over the HUD field-of-view (FOV).

In Ref. [7] Albery evaluated various display formats, including 2 orange peel formats, on the HUD of an F-16 in a fixed-base simulator experiment, aimed at resolving the unusual attitude spatial disorientation issue. The small version of the HUD-orange peel was referenced to the flight path marker (FPM) and so it moved across the HUD with the FPM moving in the various flight conditions. The larger-size orange peel was fixed, and this is the one adopted in this HDVE study. These orange peel displays were a by-product of the total investigation into the issue of SD during unusual attitudes. It turned out that the large, or fixed orange peel was preferred better than the small, moving orange peel, and gave a good recovery time.

2.4 Safety reports

An essential part of the study is the identification of key hazardous situations for VFR rotorcraft pilots in DVE conditions. For this purpose primarily the accident database of the European Helicopter Safety Analysis Team (EHSAT)[1] has been consulted. This database contains qualitative descriptions of 484 different accidents and identifies causal factors using the Standard Problem Statements (SPS) taxonomy. This taxonomy has over 400 codes in 14 different areas. EHSAT also uses the Human Factors Analysis and Classification System (HFACS) taxonomy to address human factors. This taxonomy contains over 170 codes in 4 main areas, see also Ref. [12].

2.4.1 Selection process

In order to identify the key hazardous situations a selection of the relevant accidents was made by using a selection of the SPS and HFACS codes that could be linked or related to DVE related accidents. In order to determine whether or not the accident is, or could be, related to DVE all 278 accidents found have been classified accordingly. For this classification the descriptions in the EHSAT database were used, supplemented with data from the NLR Air Transport Safety Database and, where relevant, with data from the original accident reports as published by the appropriate Accident Investigation Board (AIB).

From these 278 accidents, 96 could be linked to DVE either though DVE reported conditions or, when these were not reported, to the type of accident, e.g. Controlled Flight Into Terrain (CFIT) etc. These accidents span the period of 2000 – 2008. Note that for the years 2000 to 2005 the

[1] EHSAT is the analysis team of the European Helicopter Safety Team (EHEST) which is the European counterpart of the International Helicopter Safety Team (IHST) and falls under the European Strategic Safety Initiative (ESSI). The main objective of these teams is to achieve 80 percent fewer helicopter accidents by the year 2016, as compared to 2006 levels, see also http://easa.europa.eu/essi/ehest/.

dataset is complete; accidents at a later date have not all been included in the database yet. Of these 96 accidents, 50 were rated as a ‘probable’ (i.e. more likely, $p>0.5$) DVE-related event and 46 as ‘possible’ (i.e. less likely, $p<0.5$) DVE-related event. For those rated ‘possible’ the type of accident (e.g. CFIT) can be DVE-related but no weather/visibility information could be retrieved to confirm this.

2.4.2 Analysis and results

Based on the description and information from the 50 ‘probable’ (more likely) DVE-related accidents the following classification of accident types has been derived:

- CFIT: improper (detection of) descent;
  - During approach/landing no timely detection of the descent resulting in impacting the ground.
- CFIT: lack of ground texture;
  - Either no ground textures due to being in cloud/fog or due to snow-covered terrain resulting in loss of horizon or ground texture cues.
- Inadvertent entry into IMC;
  - The pilot became disoriented in, or close to, a cloud and lost control.
- Obstacle/Wire strike;
  - Strike with wires or other obstacles that were not (timely) seen by the pilot.
- Obstacle/Wire strike with sun/glare;
  - Unable to see a wire due to sun/glare or caused by sudden transition from shadow to bright sunlight.
- Other;
  - Various (unrelated) accidents that occurred in DVE conditions.

2.4.3 Rotorcraft classes

From the distribution of the accidents for the different accident types over the different phases of flight for the 3 classes of rotorcraft it became obvious that most of the accident events occurred for the class 1 group of rotorcraft, and most of the events occurred during the en-route phase of flight.

The first class contains rotorcraft with a MTOW up to 2250 kg. The second class contains rotorcraft with a MTOW of more than 2250 kg. up to and including 3175 kg. The third, and final, class contains the larger rotorcraft having a MTOW of more than 3175 kg. These limits are derived from EASA’s Annual Safety Review (2250 kg) and the differentiation between small and large rotorcraft as used in the respective certification specifications CS27 and CS29 (3175 kg). Class 1 rotorcraft are light single-engined rotorcraft (either piston ‘P’ or turbine ‘T’ powered) mainly operated under Visual Flight Rules (VFR). Class 2 rotorcraft contains typically single or twin-engined turbine powered rotorcraft, operated both under VFR and Instrument Flight Rules (IFR) and class 3 rotorcraft contains the multi-engine rotorcraft, predominantly operated under IFR. For each class, a typical type is included in the table with the highest estimated annual flight hours.

Because of their operational nature (mainly IFR) the class 3 rotorcraft is of less interest to the subject of this study. Combining the accidents listed above with the different classes of rotorcraft as defined in this section results in the distribution as depicted in Figure 1.

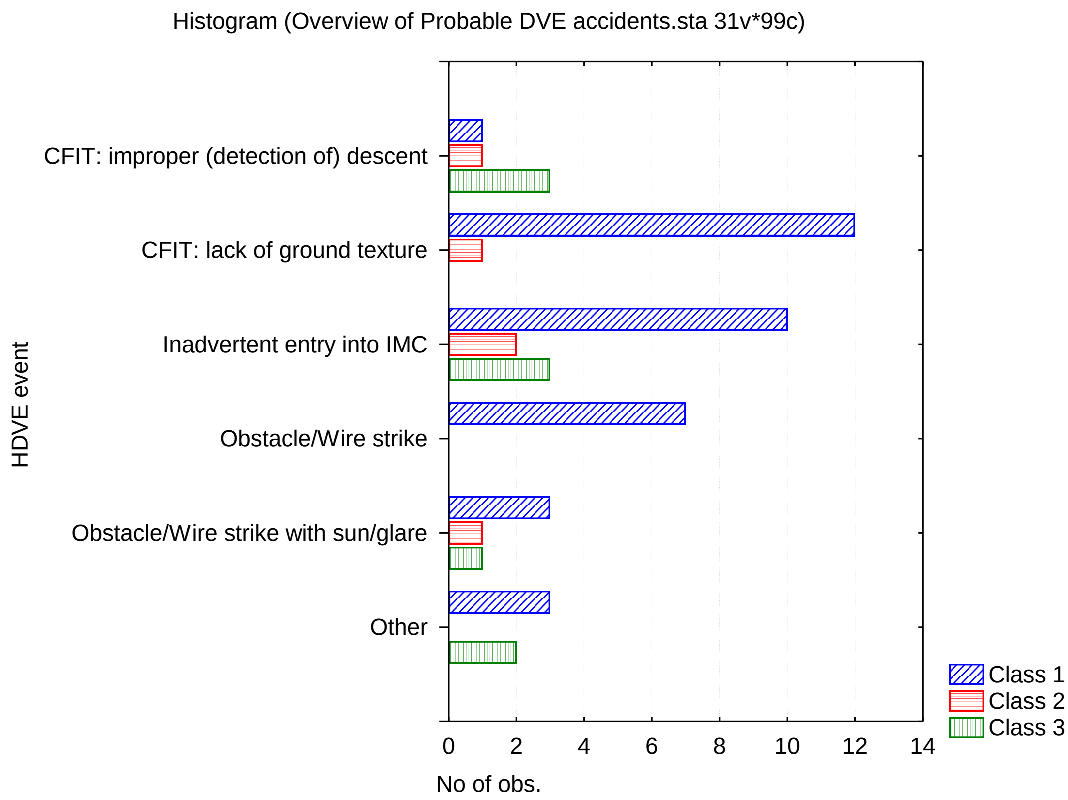


Figure 1 Distribution of accident types over rotorcraft classes

From the figure above it is concluded that the case 'CFIT: loss of ground texture' and the 'Inadvertent entry into IMC' (IIMC) (during the en-route phase of flight) have the highest rate of occurrence. The associated helicopter weight class is class 1 (light-weight). These were selected as the conditions for evaluating the visual enhancement concepts.

3 Aims and objectives

Various solutions to the problem of degraded visual environment have already been manufactured, however, they result in a substantial weight increase and cost to implement, and in many cases require the pilot to look heads-down in the cockpit to monitor a screen. EASA from the outset opted for a more fundamental approach of evaluating novel and simple visual and/or audio enhancement concepts that can be applied as a low-cost solution to the problem of safety or risk.

In the first phase of the HDVE project several enhancement concepts were defined after consultation with EASA and internal brainstorming. These concepts are described in more detail in section 4.5. From the safety situation two scenarios came up that were the most risky in this sense, viz. the Inadvertent entry Into IMC (IIMC) and the Controlled Flight Into Terrain (CFIT). Considering these two “conditions” or scenarios, the goals of this project were defined as follows:

- For the IIMC scenario:
  1. To evaluate the effectiveness of the visual enhancement concepts in terms of pilot acceptance, pilot workload, visual cues improvement and flight safety. Since the pilot’s task involves the use of the indications given by the visual enhancement concepts in the flight control loop (e.g. maintaining altitude by using the enhanced visual cues) another item of the effectiveness are the rotorcraft’s flying qualities.
  2. To determine to what extent those enhancement concepts, which depend on the hypothetical working of peripheral (or ambient) cues (viz. the Malcolm Horizon and the LED concept), are affected by the presence of a second crew member who might (possibly) interfere or block the view.
- For the CFIT scenario:
  3. To evaluate the effectiveness of the visual enhancement as well as audio enhancement concepts in avoiding hazardous conditions, i.e. approaching terrain. This too is to be rated in terms of pilot acceptance, safety, situational awareness, etc.
  4. To evaluate the effectiveness of both a visual enhancement as well as an audio enhancement concept. Would the synergy be increased by having both a visual as well as an audio concept?

Because of the scope of the work, allowed time duration and budgets involved it was not possible to go through a development cycle of e.g. testing a concept once, improve it and test it again.

As for objective 2) the addition of a second crew member to possibly interfere with the peripheral cueing issues was not carried out for a number of reasons.

With the Malcolm Horizon it would have hardly had an effect because of the wide viewing angle. Also adding a second crew member would not be appropriate because of the different cockpit size of the HPS compared to the R44, rendering the effect even less effective.
With the LED concept, since the pilot would be looking more intently at the instrument panel in case of IMC, the pilot would see less of the peripheral cues from the right-hand LED strip than from the other 2 strips because of the orientation of the instrument panel relative to the pilot's seat (slightly to the left of it). The impression arose during pre-trial runs with the LED concept that the peripheral cueing effect was not as strongly affecting the visual cueing as had been hoped for. This made the use of testing for the effect of a second crew member dubious. Finally there were budgetary reasons, since evaluation of this effect would have meant performing extra runs. The idea was to first focus on the main effects of all the concepts and later, if proven necessary, to perform additional tests to look at interactions between the various concepts.

As for objective 4) the usefulness of the visual cueing enhancement concepts was evaluated only separately and not in conjunction with the audio enhancement concept. The effect would be either a visual cue for height information when below 500 ft AGL, or a voice alert to warn of approaching terrain. In line with the above strategy to focus on main effects first, it was decided not to combine the audio with the visual enhancement concept and to register what pilots might comment on a possible combined use.

4 Methodology

In carrying out the investigation using a fixed-base rotorcraft simulator, the results depend on who the test subjects are (i.e. the pilots), which scenarios will apply and why, how the visual scenery in the simulator has been realized, what the experimental design is and the experimental factors. Of greatest importance of course are the enhancement concepts that will be tested. All of these points will be discussed in the subsequent sections.
As experimental design a so-called repeated measures or within-subjects design was used, where each pilot was offered all the visual and audio enhancement concepts on all the scenarios. In order to avoid learning effects the sequence of runs per scenario were randomized across pilots.

4.1 Subjects

Six male pilots from the Dutch General Aviation Rotorcraft Pilots Association were selected to participate as subjects in the simulations. Three of them were considered inexperienced with less than 300 hours of flight experience (min. 90h, mean 180h, max. 280h), the three others were considered experienced with more than 300 hours (min 450h, mean 744h, max.1100h). The pilots did not have an instrument rating that would qualify them to fly under IMC conditions with reference solely to the flight instruments. The selection for the two groups was randomly made from a total of 16 responses to the request for participation.
During the course of the simulations EASA participated one day with a highly experienced experimental test pilot (10,000 h) and flight test engineer. They were subjected to most of the test conditions the other pilots had also been subjected to.

4.2 Scenarios

4.2.1 Visual scene simulation

Three sceneries with accompanying flight plans were selected from the available visual scene database in the Helicopter Pilot Station, see Figure 2.
The country of Albania was selected as this was NLR's available visual data base that offered possibilities for undulated and mountainous terrain, with many different features.

The training took place in the area of Kavajě. This area has locally defined higher-detail areas.

For the IIMC scenario Lake Ohrid was selected, with the rotorcraft initially flying south alongside the western bank of the lake at 100 KIAS at about 500 ft AGL. A lake was selected for this scenario since then, while in IMC, no risk would exist to fly into a mountain, i.e. to have a CFIT case while trying to handle an IIMC.

In this scenario, visibility would suddenly drop to zero when the helicopter passed a predetermined latitude (with some random variation in the exact point). After this point, because of the closeness of mountains ashore the pilot was advised to make a left 180° turn to get out of the IMC condition. The flight would end after a certain amount of time had elapsed. IMC conditions would remain until the end of the flight.

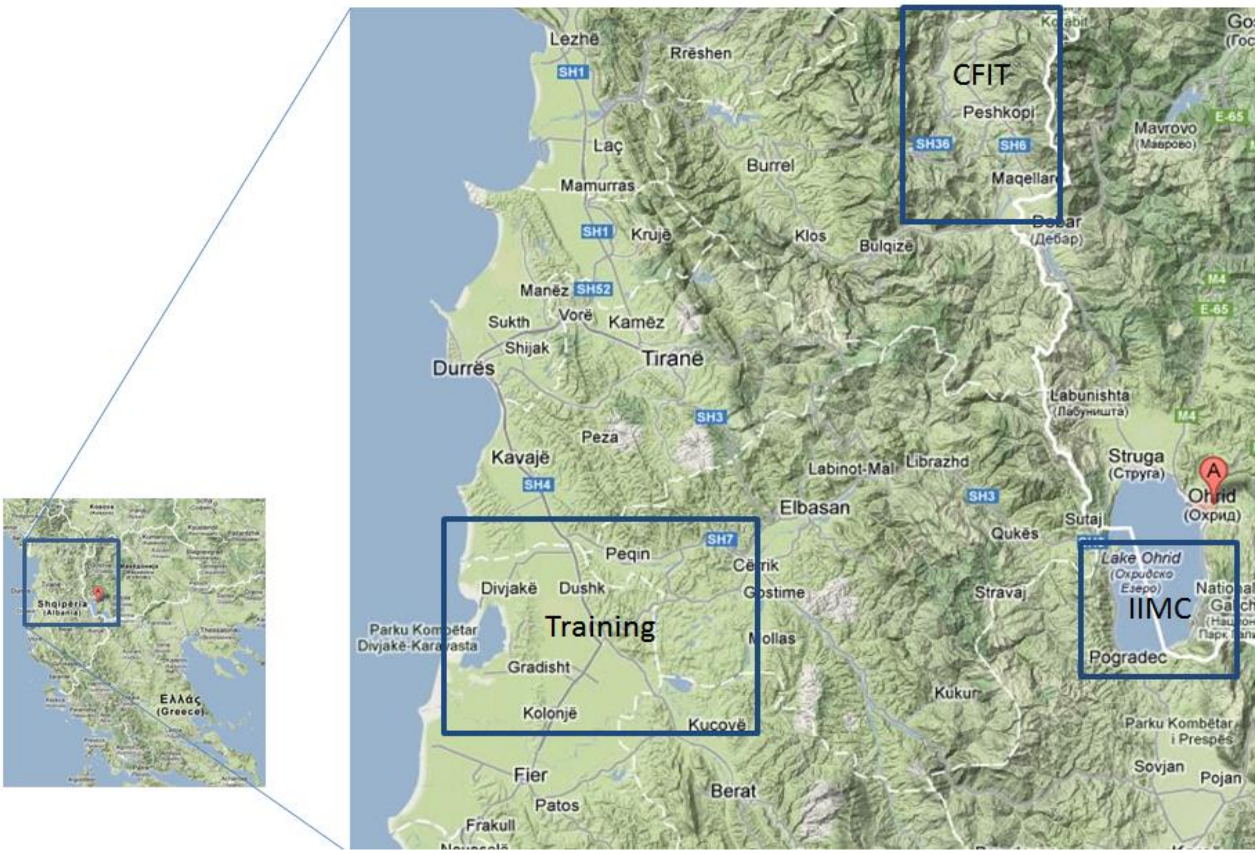


Figure 2 Areas selected for training, IIMC and CFIT scenarios.

EASA's test pilot suggested that this change from VMC to IMC be done gradually, but all pilots were expecting this bad visibility condition anyway and they might try to perform early escape manoeuvres if they would see the deterioration set in. In order to prevent this from happening, the change from VMC to IMC would therefore occur suddenly and completely.

For the <u>CFIT scenario</u> the mountainous region near Peshkopi was selected after much trial. The mountainous area was selected because of its ridges, hills, etc. In the visual scenery the ground texture was furthermore removed almost completely and a layer of snow was added to give the impression of a snow-covered world with a misty underground.

The aircraft flies to the north initially. It is a flight that would fly more or less parallel with some mountain ridges, and would pass over other ridges, while at the same time by using the reduced terrain cues and a snow cover it was very difficult to estimate height above ground, or to see the ground below at all in some cases. A cockpit view of the scenario is shown in Figure 3 where the mountain ridges can be faintly seen on the left. On this photo both the LED concept and the HUD Orange Peel were switched on.

Figure 3 View from the cockpit in the CFIT scenario with the HUD Orange Peel and LED concept

4.3 Handling qualities and rating scales

The handling qualities of the rotorcraft are likely to be affected by the presence of a visual enhancement concept, making the handling easier or more difficult, compared to the baseline aircraft, i.e. the 'no concept' case. This is because the pilot's task for the IIMC scenario was defined to maintain altitude, speed and course, which is accomplished using the enhanced visual cues continuously as well as the instrument panel visual cues, forming a visual display – pilot – control system feedback control loop. It is with this background that evaluating handling qualities only made sense with the IIMC scenario.

For the CFIT scenario the (enhanced) visual cues or audio cues were used only to trigger, as a one-off event, the pilot into taking action, rather than as a cue to be used continuously in a control feedback loop. The pilot's task was mainly to not fly into terrain, but not by increasing altitude so much that all highest terrain would be avoided. To do so would have required a climb from about 2600 ft to about 5000 ft. Any time the pilot would suspect a terrain conflict he was advised to try to increase altitude in 200 ft increments, until the situation cleared. Therefore for the CFIT scenario the visual or audio enhancement concept would be used more in the role of a trigger/detector than as a cue to be used continuously as in a control feedback loop.

In order to investigate the handling qualities, various ratings were gathered from the pilots, in terms of task performance, aircraft characteristics and the Handling Qualities Ratings (HQR) according to the Cooper-Harper Rating (CHR) scale. The pilots who participated in the experiment received ample time to become familiar with the various scales to be filled out.

4.4 Experimental test matrix

In line with the selection of the test scenarios, a test matrix was set up aimed at offering the scenarios to the pilots, without undesired learning effects. Especially for the CFIT scenario the element of surprise was important, see Table 1.

Table 1 Enhancement concept x scenario test matrix

Concept	**Test scenario**
None	IIMC
Malcolm Horizon	IIMC
LED	IIMC
HUD orange peel	IIMC
None	CFIT
HUD orange peel	CFIT
HTAWS	CFIT

Each pilot flew seven experimental runs. First the IIMC scenarios were flown with the sequence of runs randomized/balanced over the pilots in order to alleviate the “carry-over” or learning effects. Then, the three CFIT scenarios were flown, also randomized/balanced. For the CFIT runs, the objective flight data of the first run only was included in the statistical analysis, since any subsequent run would likely have been affected by the first run. This did not apply to the questionnaire data, however. In fact this made the statistical analysis follow a so-called “between subjects design”, where the subjects are made up of the enhancement concepts, in a manner indicated below.

Enhancement concept in 1st CFIT scenario	**pilot**
None	1, 4
Malcolm Horizon	2, 5
HUD orange peel	3, 6

With the EASA test pilot, and also with one (highly experienced) GA helicopter pilot the IIMC runs (except the 'no concept' case for the EASA test pilot) were also repeated with the ADI blanked out in the cockpit. This point of not having an ADI in the cockpit might be an interesting feature to investigate in conjunction with the performance of any visual enhancement concept for future tests. In earlier NLR-internal discussions this condition had been disregarded out of fear that it might be too difficult a test for the GA helicopter pilots to handle.

4.5 Enhancement concepts

4.5.1 Malcolm Horizon

This attitude enhancing device makes the pilot aware of his attitude in roll and pitch (but not quantitatively). A typical example of the Malcolm Horizon (MH) is given in Figure 4.

Figure 4 Extended horizon line or Malcolm Horizon (MH) concept

Through the whole cockpit a (red-coloured) horizon line, the "Malcolm horizon" (MH), is projected using any suitable device such as a scanning laser, reflecting off the wind screens and cockpit structure. It is worthy to note that in one of their futuristic pictures of a modern helicopter cockpit designed by Eurocopter also such a wide horizon line has been projected, see Figure 5. The (free) information was obtained from Eurocopter's website.

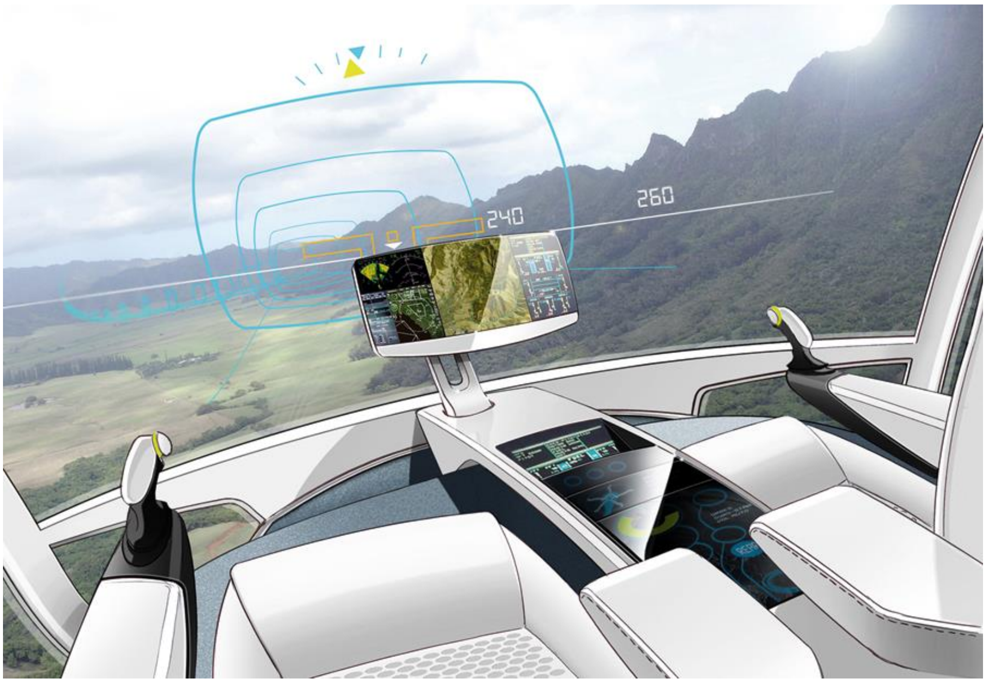


Figure 5 Future rotorcraft cockpit with Malcolm Horizon (Courtesy Eurocopter)

This Malcolm Horizon provides only pitch and roll information. Because of its "wide" angle the peripheral impression of attitude can be quite strong and compelling, which was the idea of this concept in the first place. Peripheral cues are "noted" and processed in the brain, but do not require attentional effort by the pilot to acquire.

As Figure 4 shows, in level flight in cruise the Malcolm Horizon (MH) passes just above, or through, the standby magnetic compass unit mounted on the central window style. This reference location was missing in the simulator, but was permanently added with the 4th pilot, the EASA experimental test pilot, upon his remark that such a reference indication was missing.

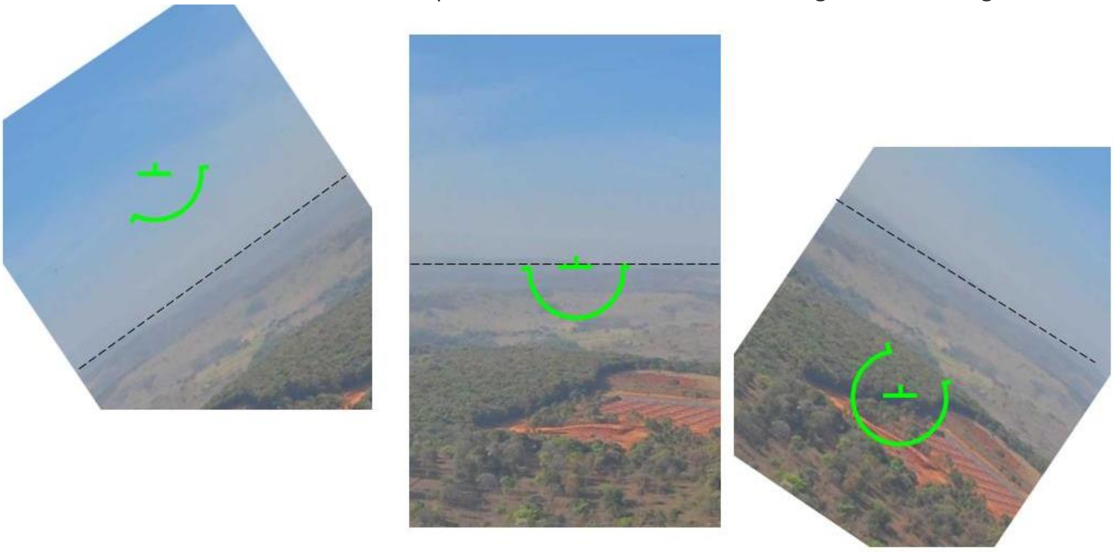
4.5.2 HUD Orange Peel

Another concept is one that has been adopted from the fixed-wing fighter aircraft domain for recovery from unusual attitudes, called the "Orange Peel", see also section 2.3. An example for a helicopter cockpit is given in Figure 6.

Figure 6 Head-Up Display (HUD) of attitude recovery using the "orange peel"

The green-coloured half circle with inverted 'T' is quite intuitive in helping the pilot to recover to level attitude from whatever attitude he might have been in. Added to the orange peel in Figure 6 is a red short line underneath the symbol, indicating approaching ground. This red line or bar appears whenever the height has become less than some reference height. When the red line passes through the inverted 'T' the rotorcraft will have reached the ground. In the implementation for the experiment the red bar appears whenever the height is 500 ft AGL or less; when it touches the Orange Peel circle the height is 200 ft AGL.

Below 3 sequences are given to show what the orange peel symbol presents in the various attitudes. The actions indicated are to be performed in order to resume straight and level flight.



a) push down and roll left *b) no action* *c) roll right and pull up*

Figure 7 Several sequences of the orange peel

The “length” of the peel, i.e. how much it encompasses the inverted T, is proportional to the pitch angle, while the “rotation” of the peel depends upon the roll angle. In the implementation in this experiment the orange peel would be complete for -30° of pitch, and will (practically) disappear at +30° of pitch. From Refs. [5], [6] and [7] it was learned that the original driver for the length of the peel was not pitch angle but rather the flight path angle. This will have some consequences, as will become evident later, see chapter 7.
Note that the symbology, presented on a (wide-angle) HUD, or else reflected from the windscreen, is fixed in position, i.e. it does not move. It was argued that in case of such a recovery from a possibly extreme attitude the symbol the pilot then needs to look at should be in the same position, regardless of the flight path, in order not to add to the confusion that may already exist. This was also preferred by F-16 pilots (see Ref. [5]).

4.5.3 LED concept

In the brainstorming performed earlier (see chapter 1) it was hypothesized that peripheral cues can be used by the pilot for orientation or attitude awareness using for example LED lights in his peripheral vision. The LED strips are lighted from the bottom (cabin floor) up to the point where it is on the horizon, seen from the pilot’s eye reference point. When in a banked attitude one strip of LEDs is then lighted further than the other strip. It was hypothesized that the pilot will use this to determine a measure of roll angle. By using a third strip in front of the pilot it was hypothesized that the differential LED information from the front and the 2 rear strips of LED lights would give pitch information in the same way. An example of such a concept is shown in Figure 8. It should be noted that this LED concept is quite novel and of a low Technology Readiness Level (TRL), therefore more research and simulations may be required for improvement of the concept.

Figure 8 Lights (LEDs) mounted in the peripheral view of the pilot

In the figure there are yellow-coloured lines of lights on the left and right edges or door styles in the cockpit, which in reality will be LEDs that are mounted on the circumference (more or less) of the cockpit frame. The boundary where the yellow lights end is the horizon.

The LEDs have been further combined in also giving a cue of the vertical speed by adding upward running (red-coloured) lights to indicate a descent condition. How well this cue is picked up was the subject of the piloted evaluation. Four of those red-coloured cues are also shown in Figure 8. Whenever there is a sink rate they appear, and the speed at which they are traveling upwards depends on the actual rate of descent. In case of a climb they will disappear.

4.5.4 HTAWS

Another type of cueing the pilot is by the use of audio signals, e.g. for approaching terrain (“TERRAIN AHEAD”), for too large a sink rate for the condition that one is in (“SINK RATE, SINK RATE”), etc., similar to what an HTAWS (‘Helicopter Terrain Awareness and Warning System’) would do.

In order to provide the proper signalling, information is needed about the flight phase, the surrounding terrain elevation, present altitude above the ground and the aircraft’s state in terms of the inertial speed vector, etc., so that the point of (imminent) ground impact can be estimated. With present-day data like a terrain database and an accurate, miniature, augmented

GPS, this type of cueing is already possible. In the piloted evaluations the usefulness of such a cueing can be investigated in isolation or in combination with the other cueing devices.
Use was made of the updated HTAWS logic as modified by the CAA, see Ref. [13].

4.6 Data registration and recordings

Two types of data were recorded, viz. objective data and subjective data.
Objective data in general were flight-parameters that were registered within the flight simulator environment, such as airspeed, altitude, pitch and roll angle, etc., as well as eye tracker data. All of this data was recorded numerically and collected by the flight simulation operating system.
The other type of data was the subjective data, consisting of the entries made in the two questionnaires that were used, viz. the In-Cockpit-Questionnaire (ICQ) after each run, and the Post-Exercise Questionnaire (PEQ) after the exercise was over. These questionnaires are described in more detail in Appendix A. Questions were asked about the workload experienced, the usefulness and acceptance of the enhancement concept, the safety level, the rotorcraft's handling qualities, the situational awareness experienced, the occurrence of a crash (and why), etc.
The data entered in the questionnaires, mostly of alpha-numeric form, were later transferred to suitable data input files that the statistics program could handle.

4.7 Eye/head movement tracking and recording

Another special type of objective data was the registration of the pilot's eye movements in all directions. At the same time head positions were also recorded, so that with the data a (more or less) absolute orientation of the pilot's direction of view could be established.
The eye tracker that was used is the Applied Science Laboratories (ASL) H6 with an Ascension Technologies magnetic head tracker (Flock of Birds). The lightweight eye tracker is a head-worn device and especially recommended in situations where it is important for participants to have freedom of movement and/or where gaze must be measured over an unrestricted field of view.

The eye tracker uses an infra-red camera, an infra-red light source and a semi-reflective visor to measure the reflection of the retina. This provides information about the position of the eye in the head (i.e. Eye Line of Sight; ELOS). Mounted on the eye tracker device is the receiver of the magnetic head-tracker. This device measures the position and orientation of the head in space (i.e. Head Line of Sight; HLOS) using the magnetic field generated by the transmitter.
A picture, taken during one of the flights with the subjects showing how the device was mounted, is shown in Figure 9.

Figure 9 Eye tracker mounted on head of test subject

For the analysis of the eye gaze data, areas of interest were defined (see Figure 10). The instrument panel area is defined by the physical dimensions of the monitor that displayed the Robinson R44 flight instruments. Right in front of the pilot, at the location where the Orange Peel would be displayed a small area has been defined, called 'Out_front'. A pilot looking straight forward will have fixations on this area. All other fixations looking outside this area will be assigned to the area 'Out_rest. The other fixations, such as inside on the kneepad or far left or far right outside, have been combined and have been assigned to the area 'Other'.

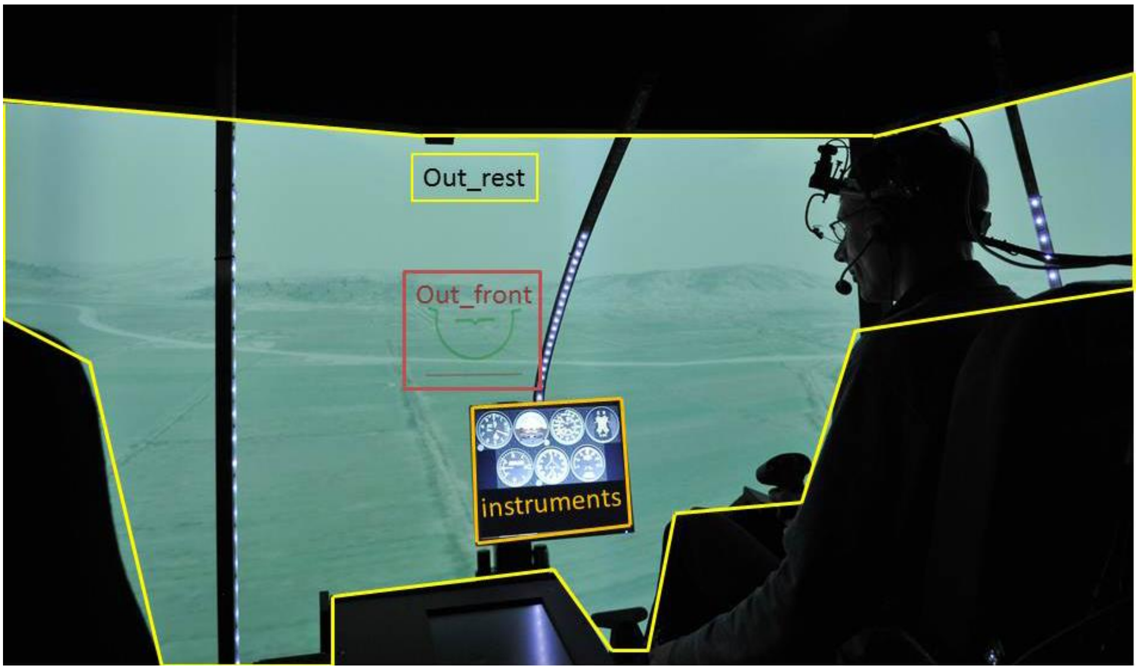


Figure 10 Distribution of focal areas in the cockpit

4.8 The HPS and field-of-view

The outside visual field-of-view of the R44 is quite different from the field-of-view of NLR's Helicopter Pilot Station 'HPS', with a wide, large helicopter instrument panel. In order to provide the pilot with a field-of-view, which better matches that of the R44, the top instrument panel was taken out and replaced by a 19" monitor, on which the R44 Raven instrument panel instrument layout was projected.

An estimate of the outside optical field-of-view of the HPS, when equipped with the reduced instrument panel, is given in Figure 11.

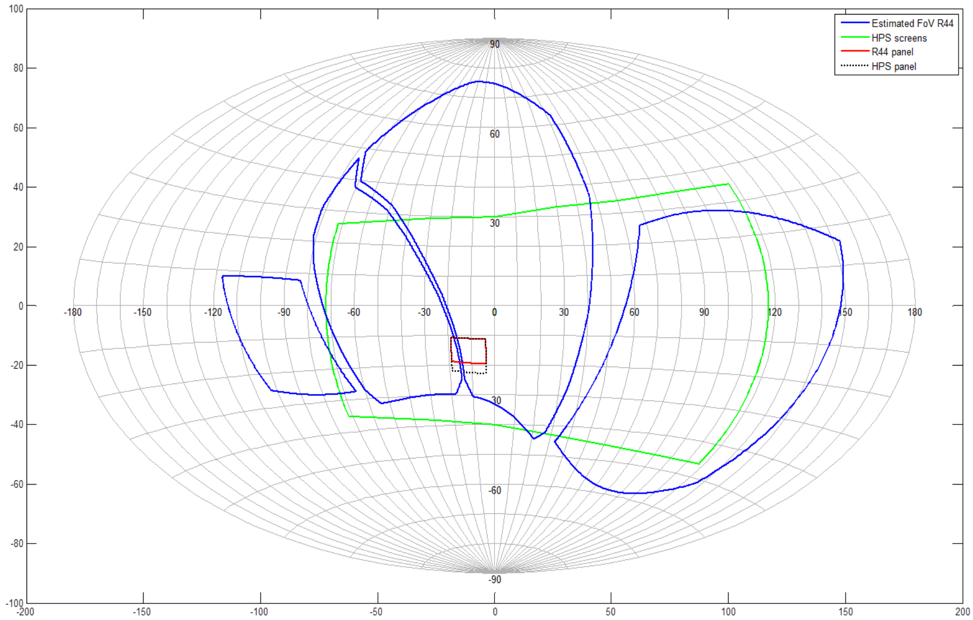


Figure 11 Optical field-of-view from the pilot's eye reference point in the HPS, with the new 19" instrument panel, relative to the R44 helicopter; HPS rotated 21.75º left relative to centerline

The R44 field-of-view is depicted by the blue lines. The projected HPS field-of-view with the new smaller panel is outlined by the green line for the maximum field-of-view, spanning a FOV of from -70° to + 115°, and in elevation from about -40° to +20° or more, with the instrument panel being represented by the red-colored rectangle. As the figure shows the R44's field-of-view is quite well approximated. Greatest deviation is at about +90° right and low, and the region beyond about +120° is not represented. Also to the left, i.e. at lateral viewing angles of -70° and further, the HPS does not provide "outside visual cues" through the left side window. The above FOV has been achieved with the cockpit rotated 21.75° relative to the center of the visual screen, so that there is more view to the right than to the left, and also downward.

5 Implementation

5.1 Flight instruments

To mimic the R44 instrument panel a 19" flat panel display was installed in the HPS. It replaced the original wide and large top instrument panel, with 4 mounted EFIS displays. The R44 instruments were simulated on the 19" display (see Figure 10).

Figure 12 Robinson R44 instrument panel to be used in the Helicopter Pilot Station. The instruments include an Attitude Director Indicator and altitude and speed dials.

5.2 Malcolm Horizon concept

When considering the installation of the Malcolm Horizon in the simulator cockpit there were quite a number of difficult and costly issues to handle. The acquisition cost of purchasing a computer-programmable laser device with a scanning laser that could be programmed to scan in the direction dictated by the rotorcraft's attitude in roll and pitch was beyond the allocated budget (and acquisition) time. In addition, in order to make it function the way it should another item to install would have been the cockpit windows upon which the laser should reflect, as the HPS cabin has no windows. It was therefore decided to "install" the Malcolm Horizon as a horizon line within the visual scenery system generated by the image generators of the simulator. A possible drawback is the more restricted range of pitch and roll angles that will be visible from the pilot's eye reference point, but the field-of-view of the R44-like cockpit was quite generous to prevent this from happening. At the same time the issue could be avoided of having to install windows in the simulator cockpit in order to provide the reflecting surface upon which the line would be projected. This is also a drawback of the real-life implementation, as the generally curved cockpit windows could considerably distort the line from being straight, apart from causing additional distracting reflections. Conversely much effort would be required to program the scanning pattern such that the horizon line would appear straight to a pilot.

Due to comments from the EASA's test pilot and the flight test engineer, a reference pitch attitude mark was mounted on the front window central frame to provide for a pitch reference in cruise flight. With the R44 the magnetic standby compass unit mounted on this frame was "normally" used for that purpose (in cruise flight), and made it easier for the pilot to find the level pitch attitude in cruise conditions by aligning the magnetic compass unit on the window styles with the horizon, or vice-versa, to align the Malcolm Horizon line with the compass. Since he was the 4th pilot to be in the simulator, pilots 4 to 7 had this reference mark available.

5.3 HUD orange peel concept

The HUD orange peel was installed within the visual graphics system as originally planned. The display format was obtained from other projects (e.g. see Refs. [5], [7]), where a much more complicated display was used with several tic marks, digital read-outs, etc. For the purpose here the HUD had been de-cluttered and all the extraneous information removed. The display used looked as shown in Figure 13. Only for one side, i.e. the right-hand seated pilot, was the display generated.

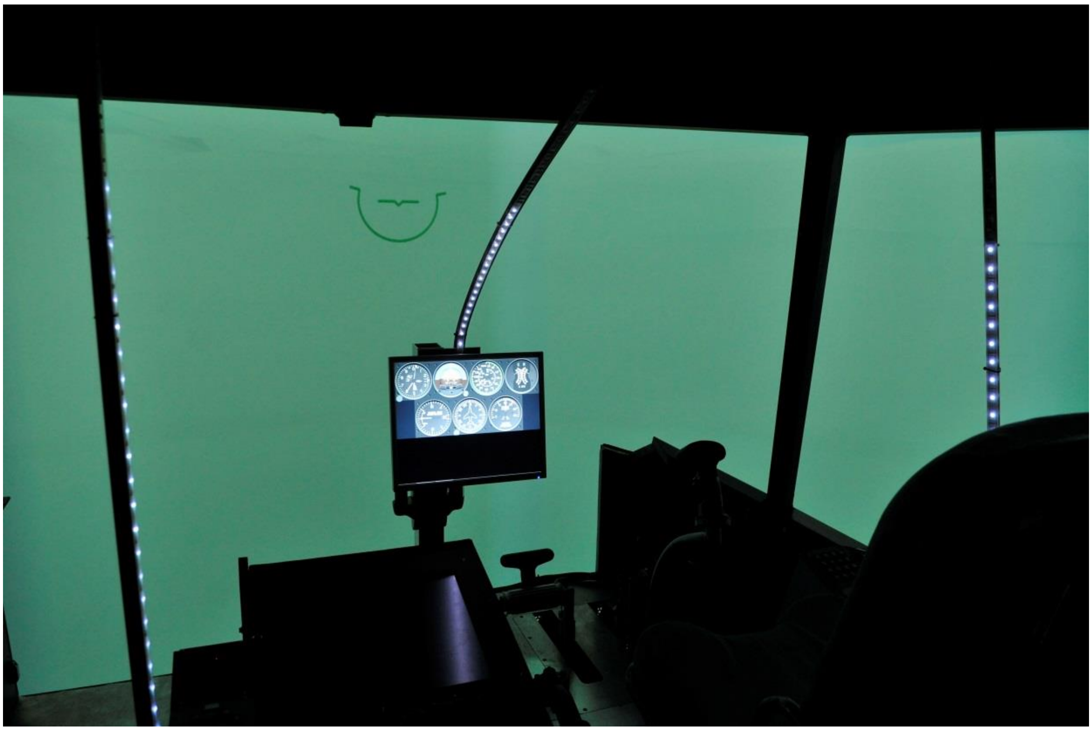


Figure 13 HUD Orange Peel symbology (together with LED strips)

5.4 LED concept

From the concept discussed in §4.5.3 three strips, or bars, were mounted in the HPS cockpit; one to the right of the pilot, one to his left and one in front, behind the instrument panel. The mounting distances from the pilot were in accordance with the R44 cockpit location of the window styles. Onto these bars the LED strips were attached, from the floor to the roof of the cabin. These bars were not rigidly attached to the simulator structure, so that, if need be, they could easily be relocated at other positions. The lowest programmable light intensity of the LEDs was used, but still they were very bright in the flight simulator environment.
In the implementation the yellow-coloured lights were now white-coloured, see Figure 14 below.

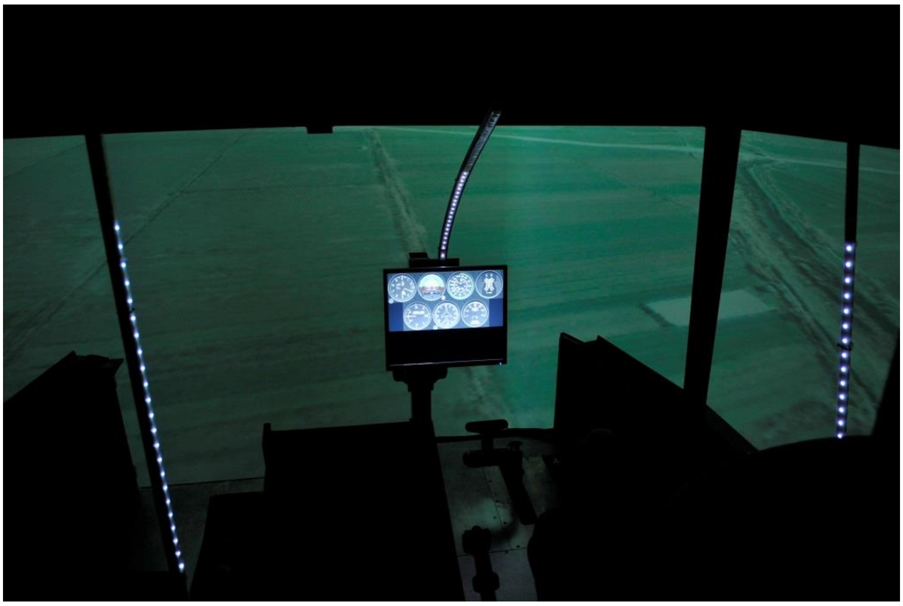


Figure 14 LED concept of three strips/poles in the cockpit

The moving running lights are not coloured red but amber, see below in Figure 15.

Figure 15 LED concept with amber-colored upward-traveling lights

5.5 The HTAWS concept

Originally an adaptation of an existing Ground Proximity and Warning System (GPWS) software was used, in accordance with the warnings discussed and specified in Ref. [13]. It turned out, when testing the system in the mountainous database of the scenarios, that there were too many or too few alerts. It was ultimately decided to introduce the so-called Time-To-Impact 'TTI', which in the simulator environment is computed as the ratio of the distance-along-the-line-of-sight to the impact point (computed within the simulation software environment), divided by the inertial speed. If TTI becomes less than 30 seconds, but more than 20 seconds, the alert "TERRAIN AHEAD' will sound. When TTI becomes 20 s or less the warning "PULL UP" is given. As soon as the condition clears the respective voice alert ceases. Apart from this type of "forward-looking" alerts also other modes were available, e.g. "TOO LOW TERRAIN", where no ground impact will occur but considering the speed of the flight (more than 90 KIAS) the altitude clearance is quite low (100 ft or less).

Because they do not need a combining glass, reflective windows and/or symbol generator projectors, the HTAWS as well as the LED concepts are relatively cheap compared to the other visual enhancement concepts. Also in terms of implementation they came closest to the real world.

6 Results

The results have been broken down first by scenario and then by topic, i.e. pilot acceptance, workload, handling qualities, situational awareness, etc., which will then show the effect of the various enhancement concepts on these topics. In this way an easy comparison of concepts can be shown relative to one another or to the 'no concept', or 'baseline' case. In section 6.1 results for the IIMC scenario are given, while in section 6.2 results are given for the CFIT scenario. The Visual Cue Ratings and eye tracker data results are given in sections 6.3 and 6.4 respectively.

6.1 IIMC scenario

The results in this section will be applicable only for the IIMC scenario, the test scenario where inadvertent entry into IMC is evaluated. Only *visual* enhancement concepts have been evaluated on this scenario.

6.1.1 Effect of visual enhancement concepts on pilot acceptance

The pilot gave concept acceptance ratings per run when flying with a concept. A histogram of values per concept is given in Figure 16.

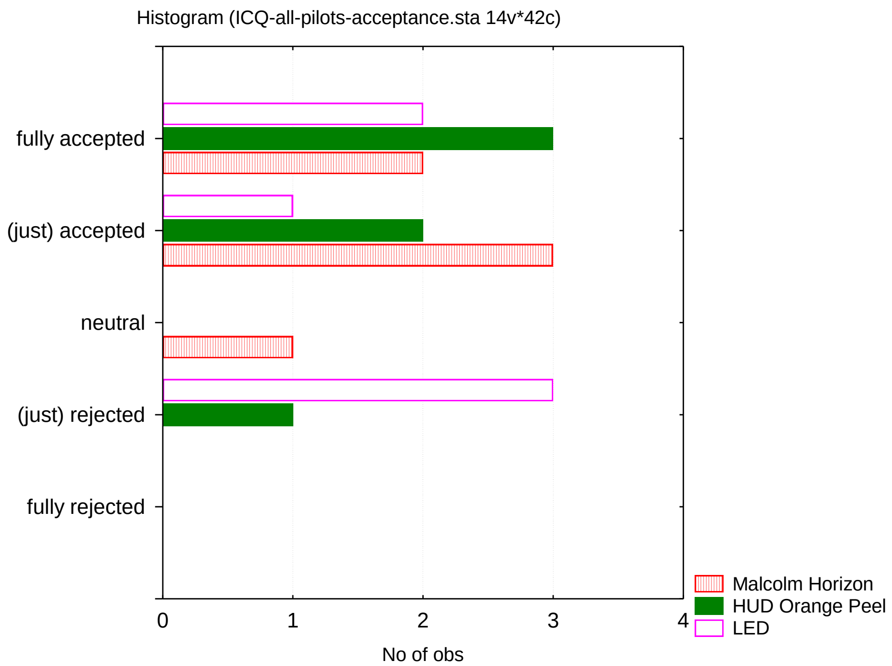


Figure 16 Pilot's acceptance of enhancement concepts per scenario

The LED acceptance was significantly less ('(just) rejected' as a modal response) than the Malcolm Horizon or the HUD Orange Peel, although there was no statistically significant difference (p>0.1). Modal acceptance ratings were '(just) accepted' for the Malcolm Horizon, 'fully accepted' for the

HUD Orange Peel, and '(just) rejected' for the LED concept, although there were also 2 ratings with 'fully accepted' so the pilots were not unanimous.

Also in the Post-Exercise Questionnaire (PEQ), pilots expressed a clear preference for the HUD Orange Peel or Malcolm Horizon above the LEDs, with the HUD Orange Peel being slightly better accepted than the Malcolm Horizon, see Figure 17.

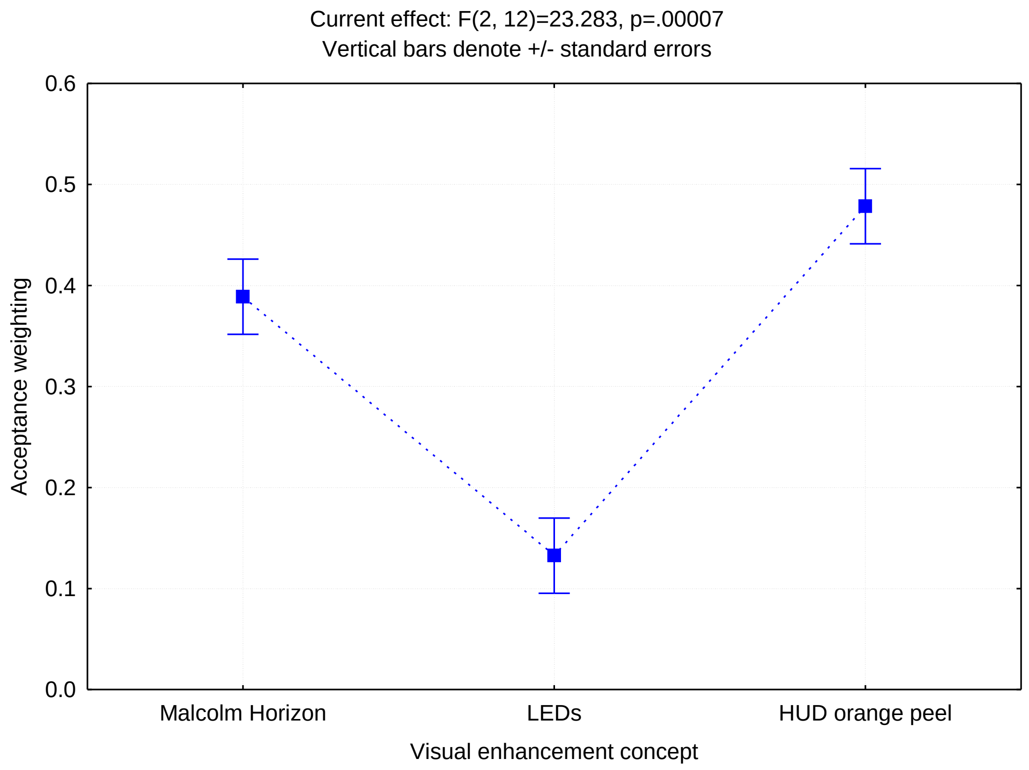


Figure 17 Comparative acceptance weighting of visual enhancement concepts

The LED concept was very negatively received. The peripheral cues it was supposed to give did not materialize, and the concept itself was sometimes very compelling. What were appreciated were the upward moving cues for sink rate. One remark from a pilot was to also add downward going climb rate cues. Because of the strong negative acceptance the novel LED concept obviously needs improvements considering the low TRL at the moment.

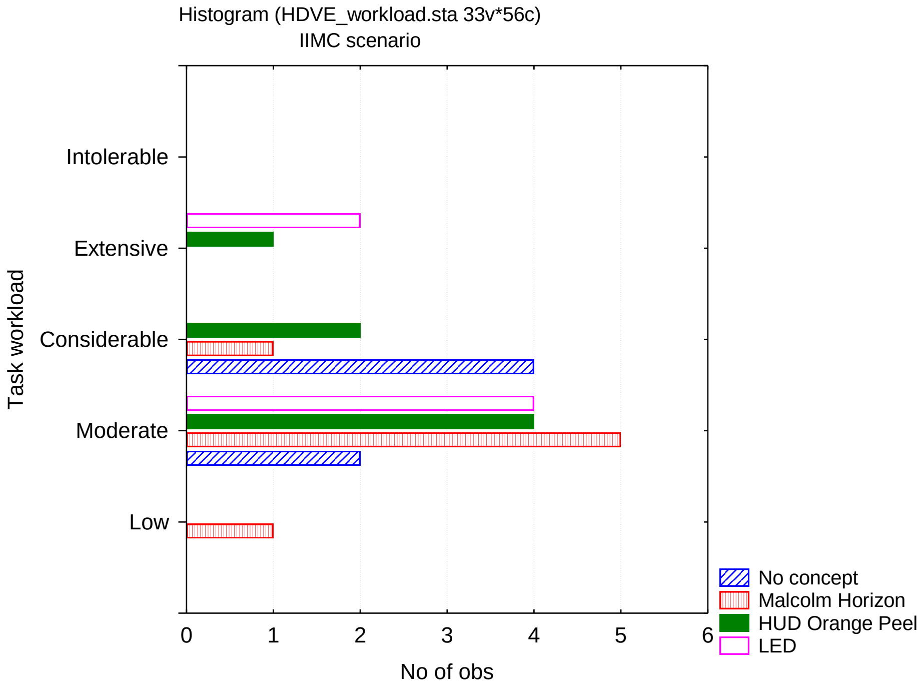
The main pilot comments about acceptance of the concepts for this scenario are given per concept in Table 2.

Table 2 Pilot comments on acceptance of concepts. IIMC scenario

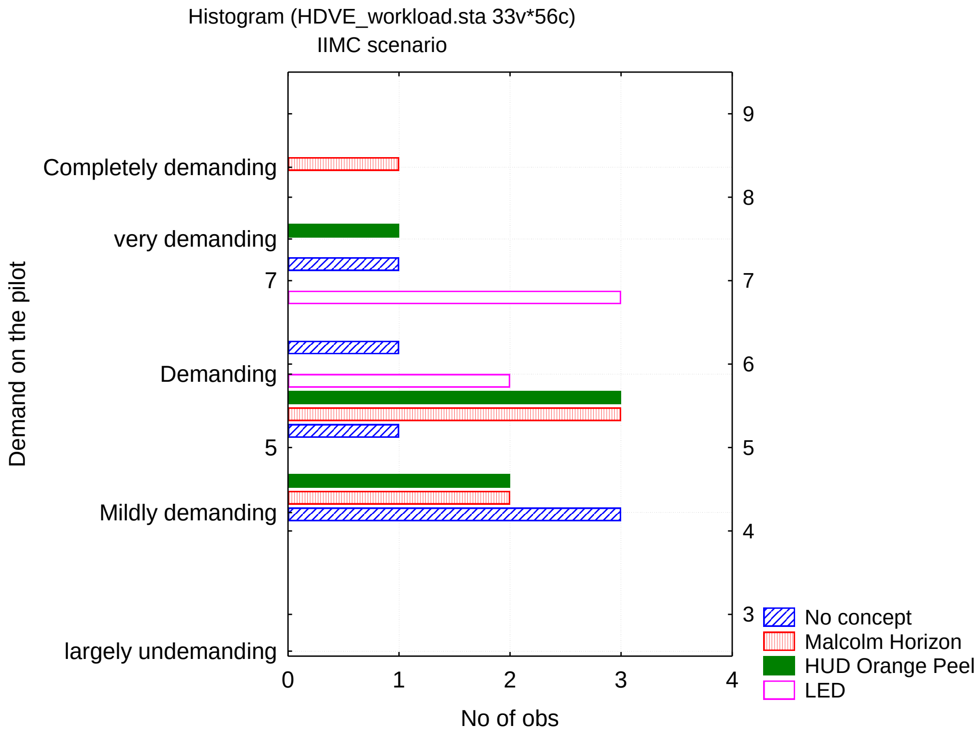
Enhancement concept	Why (not) accepted?
Malcolm Horizon	Quiet, it helps with both IMC and VMC. In IMC you fly on panel, but can see the line well from the corner of your eye
	good visibility of the system (Place projection)
Malcolm Horizon	Line too thick + compelling. Additional ±5º pitch scale needed
	Easy to use. System is helping to find horizon easily
HUD orange peel	I concentrated more on the cockpit instruments (than on the HUD)
	Accepted in VMC. In IMC not needed, but it is not a hindrance
	Small and not too distracting in visual enhancement
	Very good system and controllable
	Lack of pitch ref. in turns. Tendency to pitch PIO. Lack of roll reference.
	You get a sense of chasing (after the symbol). Need to compensate occurs.
LEDs	Descending info ok. Horizon info is minimal
	Addition for IMC. Rejected for VMC
	Not enough horizontal cues. Sink rate and roll satisfactory.
	Easy in use
	Simple but effective warning
	Not very good visibility and too much workload
	Does not inform. Too bright, sensitive and compelling
	Lot of distraction

6.1.2 Effect of visual enhancement concepts on pilot workload

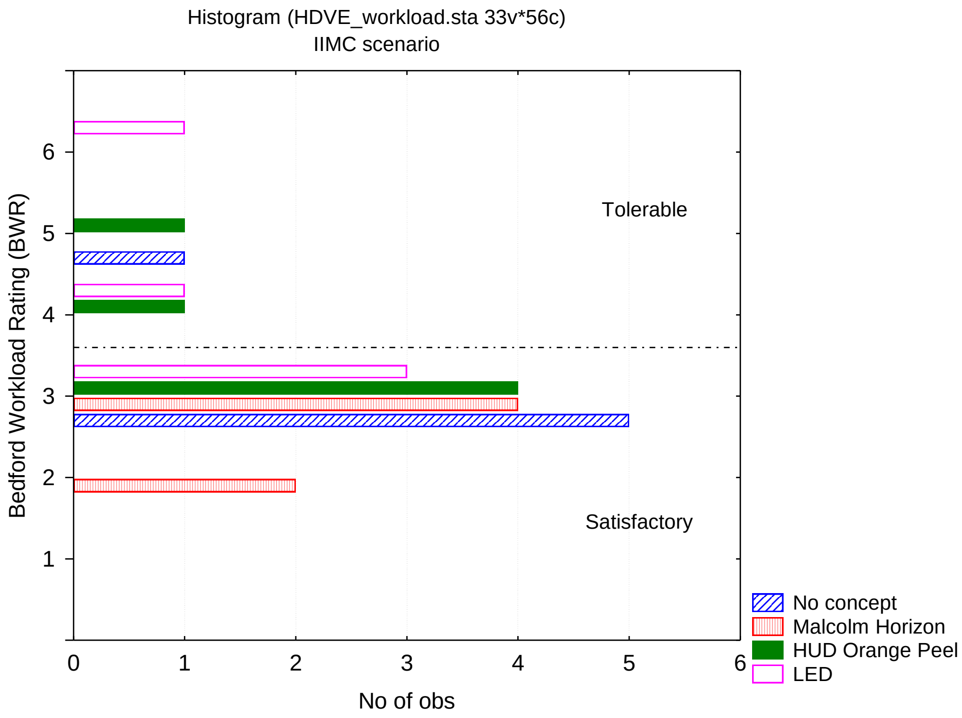
For pilot workload 3 measures were taken using the questionnaire, viz. the ordinal-scaled 'task workload', the interval-scaled 'demand-on-the-pilot' derived by McDonnell (Ref. [1]) and the ordinal-scaled 'Bedford Workload Rating' (BWR). Unfortunately they did not all correlate well among one another, therefore, for an overall picture of the effect of enhancement concept on workload all 3 workload measures are shown, see Figure 18 a) to c).



a) task workload



b) demand on the pilot



c) Bedford Workload Rating (BWR)

Figure 18 Pilot workload measures per concept

Perhaps a bit hard to see, but the Malcolm Horizon required slightly less task workload in this IIMC scenario than the 'no concept' case. The other concepts had no statistically significantly lower workload than the 'no concept' case.

The one outlying demand-on-the-pilot rating of 'completely demanding' (8.5 on the linear scale) in Figure 18b) was a run where there was a narrow escape from hitting the ground due to near loss of control with the Malcolm Horizon. Apparently the demand-on-the-pilot scale picked this up, as the pilot did not give correspondingly high values for the other workload scales. When looking at 'modal' values (the highest histogram values per concept) the following table results:

Concept	Task workload	Demand on the pilot	BWR
None	Considerable	Mildly demanding	3
Malcolm H.	Moderate	Demanding	3
HOP	Moderate	Demanding	3
LED	Moderate	Demanding	3

So "on average", compared to the baseline the task load goes down with a concept, whereas the demand on the pilot goes up, and the BWR remains unchanged.

6.1.3 Effect of visual enhancement concepts on handling qualities

The Cooper-Harper Rating (CHR), associated with flying qualities, can only be given after a check against the performance level had been achieved, because the CHR relates to desired or adequate performance levels. These specified levels are given below in Table 3.

Table 3 Specification of desired and adequate performance levels

Parameter	Desired performance	Adequate performance
Speed	±10 kt from cruise (100 KIAS)	±20 kt from cruise (100 KIAS)
Altitude	± 100 ft from starting altitude	±200 ft from starting altitude
Course	±15° from intended track	±30° from intended track

Actually the CHR scale does not ask: "has adequate performance been achieved", for example, but "is adequate performance ***attainable***", so there is some room for interpretation by the pilot, which could lead to variability in rating the handling qualities.

For the non-test pilots the Cooper-Harper scale was new to them, so time was taken to introduce the scales and what it stands for. Nevertheless it was observed that the application resulted sometimes in improper values of CHR, with a less than desired correlation with the values from the helicopter characteristics. Obviously, the EASA test pilot was very familiar with the CHR and his ratings have been superimposed on the other CHR ratings, see Figure 19 (Note that the test pilot did not fly all conditions).

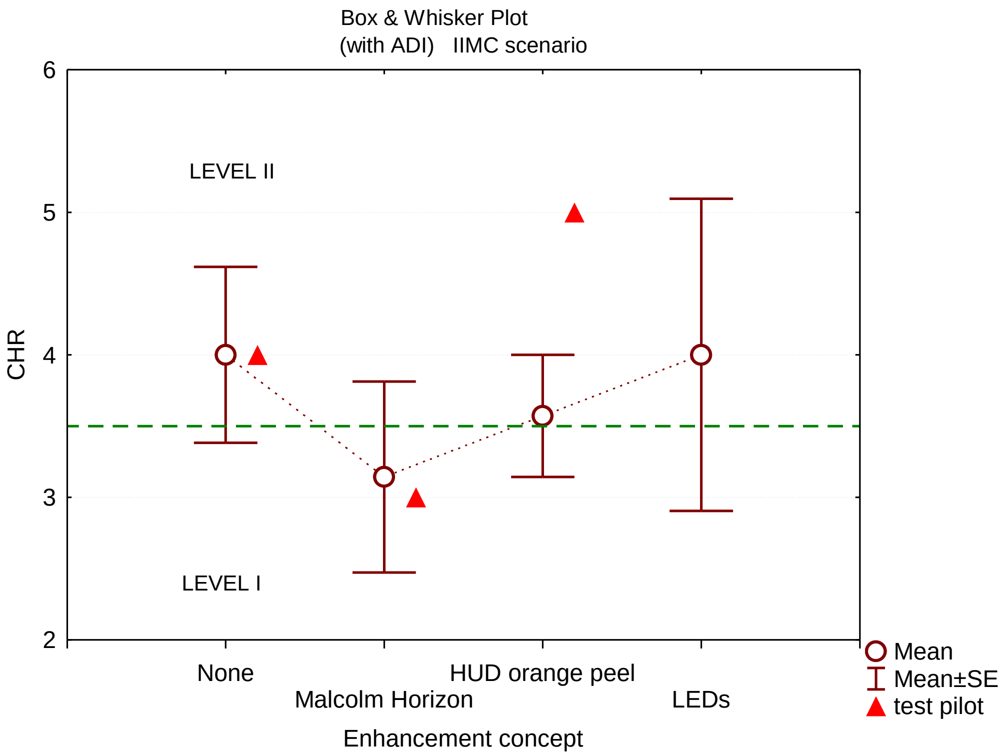


Figure 19 Cooper-Harper Ratings per enhancement concept; IIMC scenario (lower is better).

The statistical tests indicated at least a statistically weakly significant ($p<0.1$) main effect of enhancement concept on the handling qualities of the vehicle, the main contribution being a significant ($p<0.05$) improvement in handling qualities for the Malcolm Horizon compared to the 'no concept' case. This trend was also confirmed by the ratings of the test pilot (see triangles). This means an improvement from CHR=4, which is handling qualities Level 2, to CHR = 3, which is Level 1 handling qualities.

Noteworthy is that for the HUD orange peel the test pilot scored a much higher (worse) CHR of 5 than the average value for that concept of about 3.5 from the other 6 pilots. The main reason was the test pilot's comment that this concept tended to drive him into a PIO (Pilot-Induced Oscillation), which was not evident with the other concepts. The other non-test pilots did not notice this PIO tendency clearly except one pilot. Had this phenomenon not occurred then the rated handling qualities would have been at least as good as with the Malcolm Horizon.

6.1.4 Effect of visual enhancement concepts on situational awareness

Another operationally important score is how the visual enhancement concept would affect the situational awareness and, if so, to what extent. This data was also collected in the same In-Cockpit Questionnaire.

A histogram of the ratings on situational awareness is shown in Figure 20 per concept.

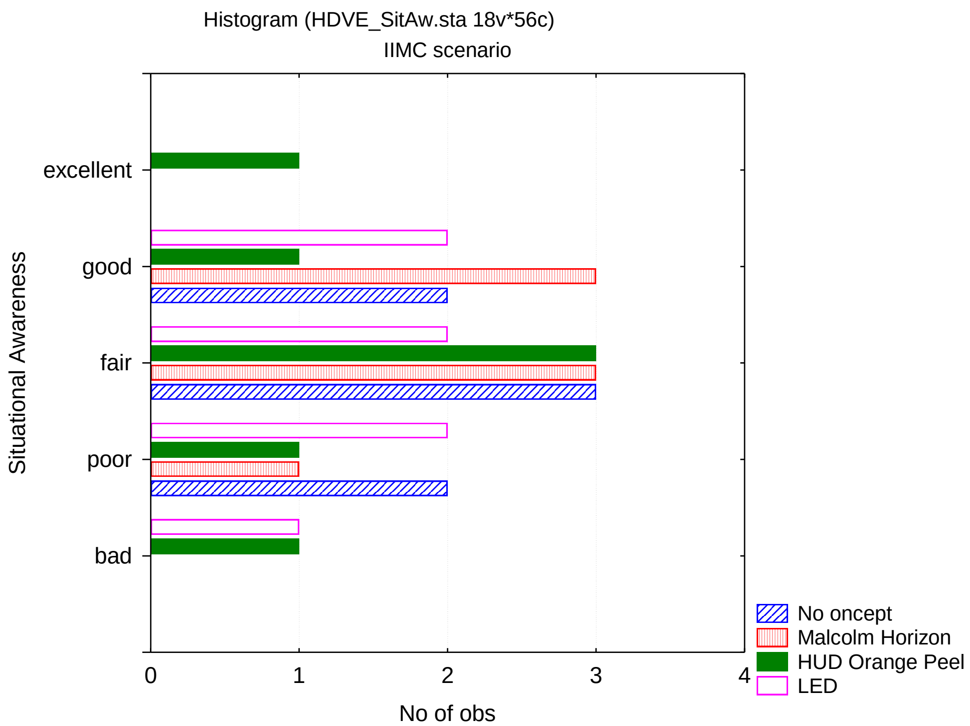


Figure 20 Situational awareness per enhancement concept

The enhancement concept did not have a statistically significant effect on the situational awareness for this scenario. The only 'excellent' rating given was for the HOP concept, but it was also given the worst rating ('bad'), together with the LED concept. On average the situational awareness score varied widely for each concept, from excellent/good to poor/bad.

6.1.5 Effect of visual enhancement concepts on flight safety

6.1.5.1 Safety ratings (subjective)

Various safety indicators were developed in the project, one such parameter being the Flight Risk '*FR*', computed from the mean and standard deviation of height-above-ground h_R, airspeed *IAS*, rate of descent *ROD*, and flight envelope limits for roll and pitch angles of $|\varphi|<90°$ and $|\theta|<30°$ respectively.

The parameter was computed from the statistical data, using the mean, standard deviation, minimum and maximum values, and using the assumption of normality of the data, as follows:

$$\begin{aligned} FR &= prob[(h_R \leq 0) \cap ((IAS > 30\ \text{Kt}) \cup (ROD > 1000\ \text{fpm})) \cup (|\varphi| > 90°) \cup \\ &\quad (|\theta| > 30°)] \\ &= p(h_R < 0) * p(IAS > 30\ Kt \cup ROD > 1000\ fpm) + p(|\varphi| > 90°) + p(|\theta| > 30°) \\ &= p(h_R < 0) * [p(IAS > 30Kt) + p(ROD > 1000) - p(IAS > 30) * p(ROD > 1000)] \\ &\quad + p(|\varphi| > 90°) + p(|\theta| > 30°) \end{aligned} \tag{1}$$

The product rule applies formally when the probability events are independent, which is assumed to be the case.

In other words, when the radio altitude is less than or equal to 0 ft [2] ***AND*** the airspeed at that moment is greater than 30 KIAS ***OR*** the rate of descent ROD is greater than 1000 fpm, ***OR*** the bank angle is greater than ±90° ***OR*** the pitch angle is greater than ±30° a crash is supposed to have occurred: *FR*=1. If deemed necessary another limiting value than 30 KIAS or 1000 fpm may be specified.

To compute the individual probabilities $p(h_R < 0)$ and $p(IAS > 30\ Kt)$ for example, a Normal probability distribution is assumed. The mean values and standard deviations have been computed for the relevant flight phases. For the probability of h_R being less than zero, since per flight segment the minimum values of the parameters are also known, the probability is computed as follows:

[2] In the simulator environment a height of 2 ft is taken into account for the landing skids being 2 ft beneath the center-of-gravity

$$p(h_R < 0) = \begin{cases} INormal(0, \bar{h}, \sigma_{h_R}) & h_{R_{min}} > 0 \\ 1 & h_{R_{min}} \leq 0 \end{cases} \quad (2)$$

Here *INormal*(x, m, sigma) is the integral from –infinity to x (=0[1] in this case) of the Normal distribution function with mean 'm' and standard deviation 'sigma'. A similar expression is used for the other probabilities.

Where necessary this Flight Risk '*FR'* can be used together with other flight parameters in subsequent analyses. As a check, for all the crash cases that occurred the computed Flight Risk was also exactly computed equal to 1.0.

Also a subjective safety rating was given by the pilot in the questionnaire, of which a histogram is shown in Figure 21.

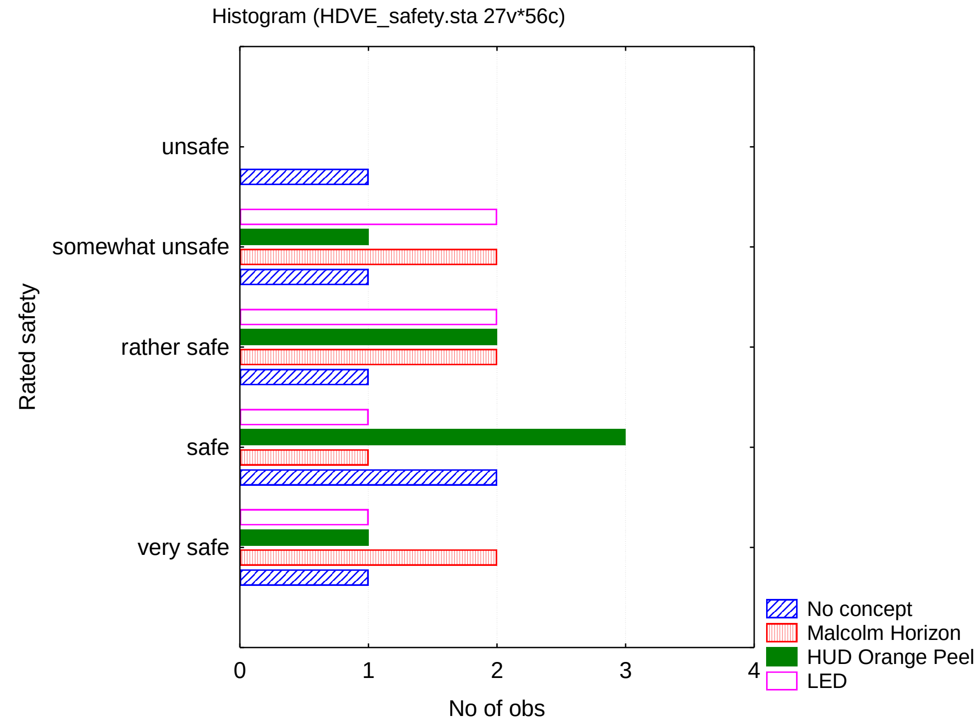


Figure 21 Rated flight safety per enhancement concept. IIMC scenario

As it turned out the visual enhancement concept had no statistically significant effect on rated safety. The LED concept seemed to be rated somewhat more unsafe than the other concepts, but the differences are not statistically significant.

Just to show what the Flight risk looks like a histogram of values per concept is shown in Figure 22.

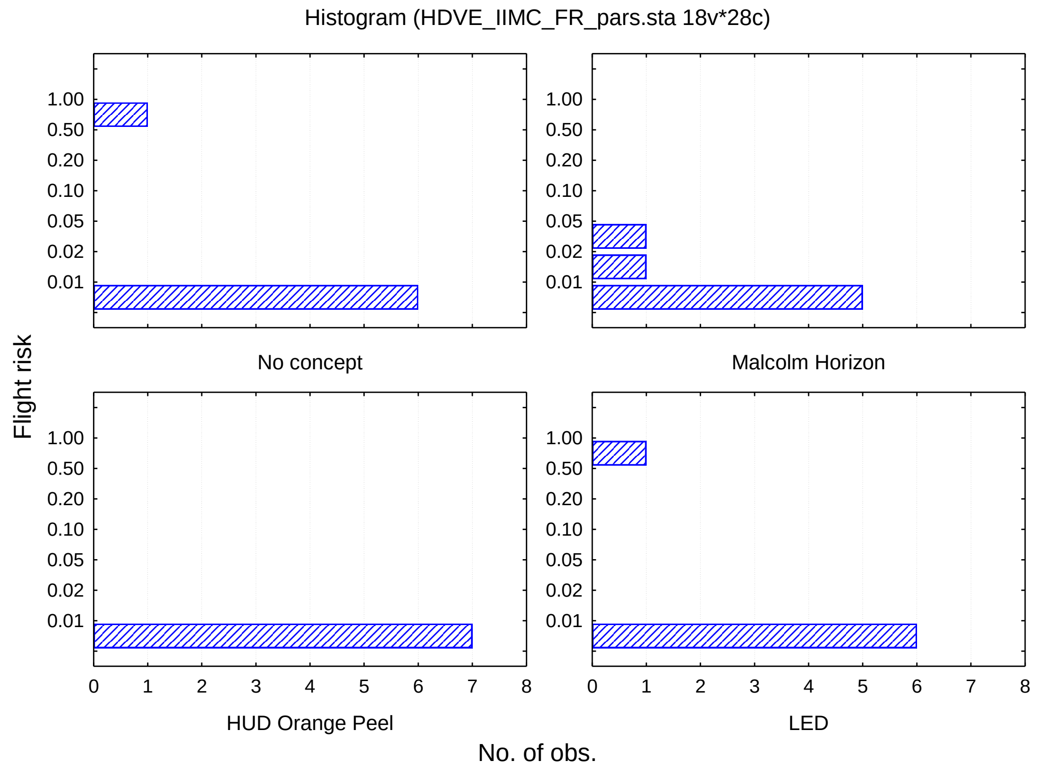


Figure 22 Flight risk per visual enhancement concept. IIMC scenario

Clearly there are two cases of a crash, i.e. one with the 'no concept' case and one with the LED concept, showing up in the Flight Risk (*FR*=1). For the other runs the Malcolm Horizon had a few occurrences of non-zero values of between 0.01 and 0.05, while most of the values of *FR* that occurred were 0.01 or less.

6.1.5.2 Accident rates

Associated with safety is the number of crashes that occurred. Only 2 crashes occurred, see also the previous section.

One crash occurred with 'no concept' and one occurred with the LED concept, both of which were typically a loss of control situation.

6.2 CFIT scenario

The results of the various items in this section specifically apply to the CFIT scenario. The focus is not so much on handling qualities, maintaining controlled flight, etc., but on avoiding collision with terrain even while having cues available. The stress that might develop in the cockpit therefore is not so much related to maintaining control but more in how to handle terrain features. It must also be pointed out that for all the pilots except one flying in a mountainous environment was quite new to them. The one exception involved a pilot who had done some mountain flying (training) privately.

6.2.1 Effect of visual/audio enhancement concepts on pilot acceptance

The pilots gave concept acceptance ratings per run when flying with a concept in this CFIT scenario. A histogram of values per concept is given in Figure 23.

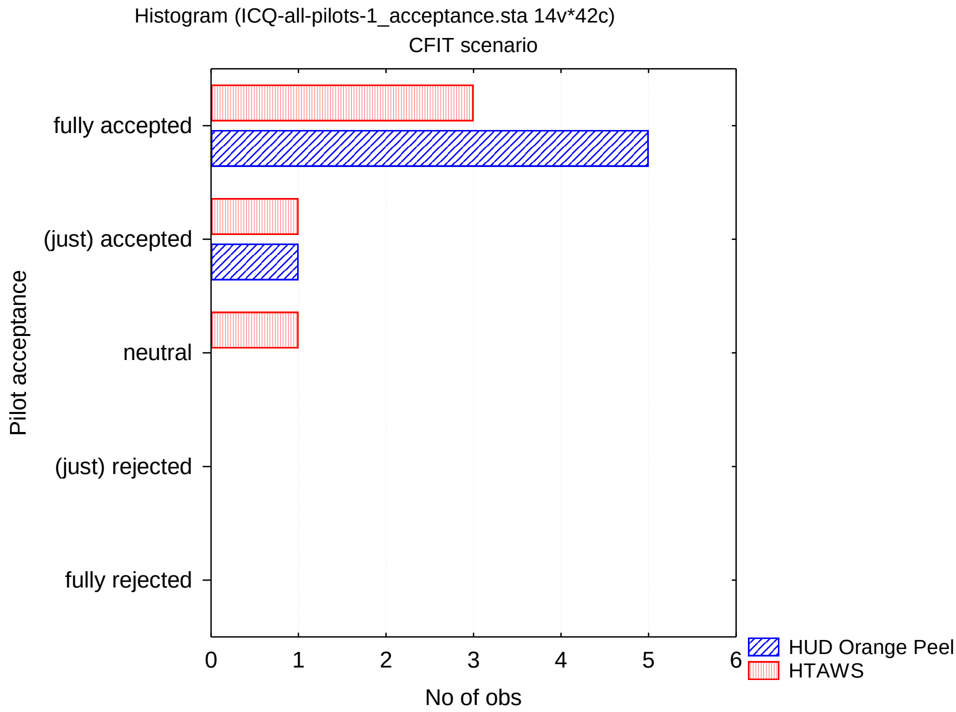


Figure 23 Pilot's acceptance of enhancement concepts. CFIT scenario

For this scenario the HTAWS was accepted just a little bit less than the HUD Orange Peel, but there was no statistically significant difference. The modal acceptance ratings of the HOP and the HTAWS were 'fully accepted'. There was one extra rating obtained with the HOP than with the HTAWS, hence the small difference that shows up in the figure. The one 'neutral' acceptance rating for the HTAWS was given because of an HTAWS missed alert that resulted in a "classic" CFIT.

Pilot comments about the acceptance of the concepts in this scenario are given in Table 4.

Table 4 Pilot acceptance comments on concepts in CFIT scenario

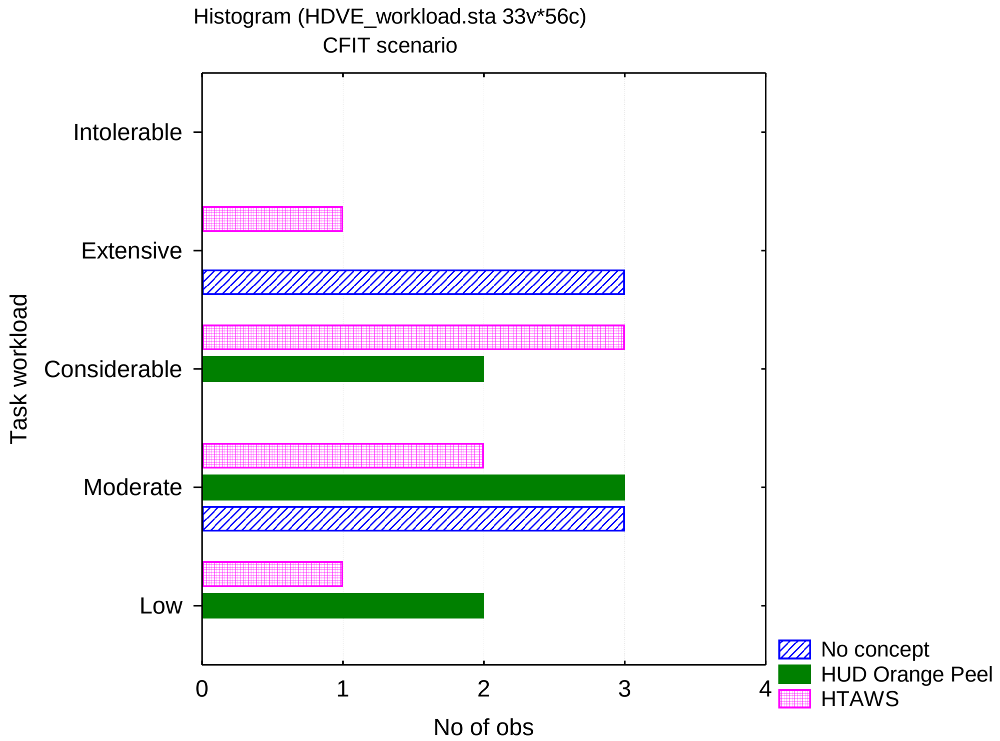
Enhancement concept	Why (not) accepted?
HUD orange peel	Red line indicates well
	It certainly helps. Stress level goes up as soon as red line appears suddenly. Perhaps it should be faded in?
	Also in mountainous terrain an adequate aid.
	clear and easy
	Very confidence building. Good rate of closure. Good altitude control in haze, degraded visual conditions. Good vertical AGL awareness.

Enhancement concept	Why (not) accepted?
	Easy in use
	Very good system and controllable
HTAWS	Good info on separation from the ground
	good indication voice
	Simple but effective warning

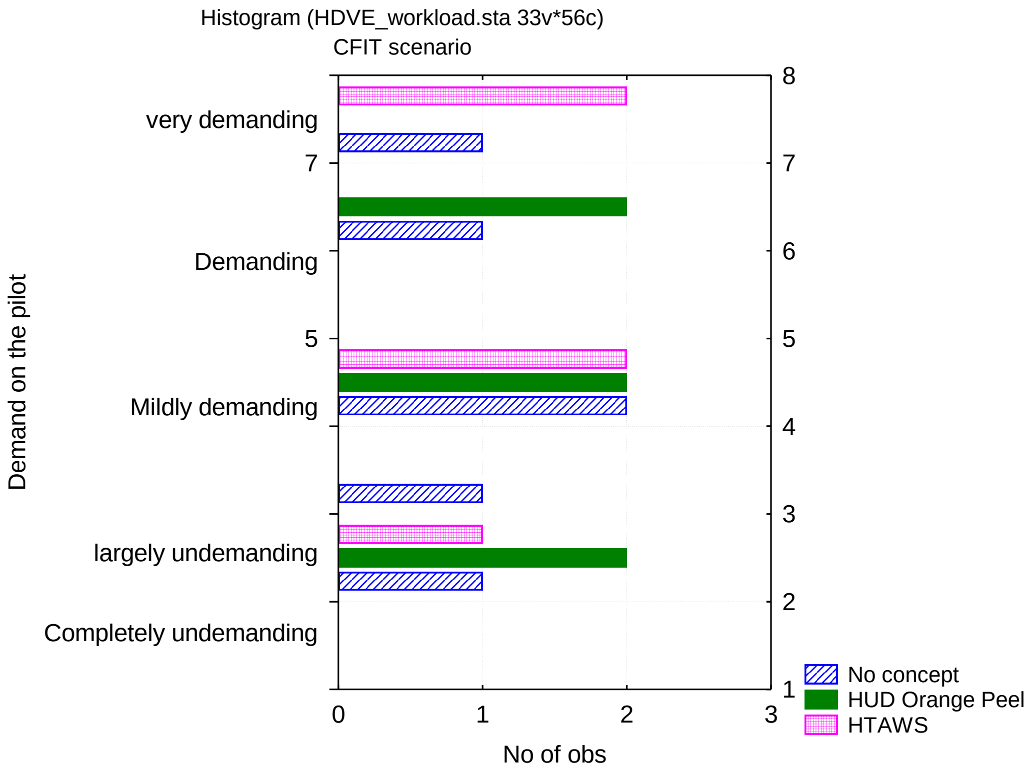
All pilot comments were praising the HTAWS as well as the HUD Orange Peel, although one pilot noted an increase in stress level as soon as the red ground bar came into view.

6.2.2 Effect of visual/audio enhancement concepts on pilot workload

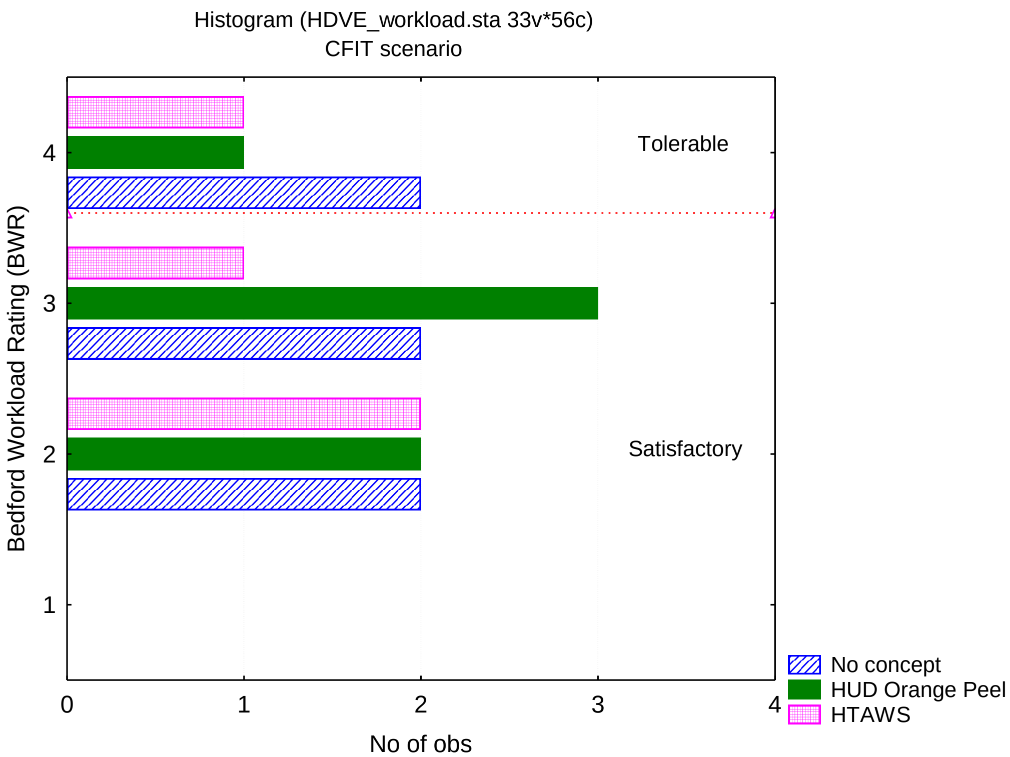
For an overall picture of the effect of enhancement concept on pilot workload see Figure 24a) to c) for the 3 workload measures.



a) Task workload



b) demand on the pilot



c) Bedford Workload Rating (BWR)

Figure 24 Pilot workload measures per concept. CFIT scenario

The task workload did not differ statistically significantly between concepts, despite small differences. Modal response of task workload was between ‘moderate’ and ‘extensive’ for the ‘no concept’ case, it was ‘moderate’ for the HOP, and ‘considerable’ for the HTAWS. But the variation about these modal values is considerable too.

Also the demand-on-the-pilot did not differ between concepts. The only significant effect here was that the low-experienced pilot group had a statistically significantly higher demand (‘demanding’ on average) than the high-experienced pilot group (‘mildly demanding’ on average) had. Reason for this is unclear, but it is likely to be simply due to pilot experience. Also the BWR did not differ either between concepts.

So, apart from the level of flight experience, there was no effect of the visual or audio concept on the pilot workload. What is striking to see are the fairly high levels of workload for all workload measures that occur with this scenario, apparently induced by the stress of not knowing when and where ground obstacles show up or, if they do, what to do next. As one pilot noted, “*the stress level goes up as soon as the ground bar appears*” (with the HOP). Still the HOP did not score higher in workload than the HTAWS did.

6.2.3 Effect of visual/audio enhancement concepts on situational awareness

A histogram of the values for the rating on situational awareness is shown in Figure 25 per concept.

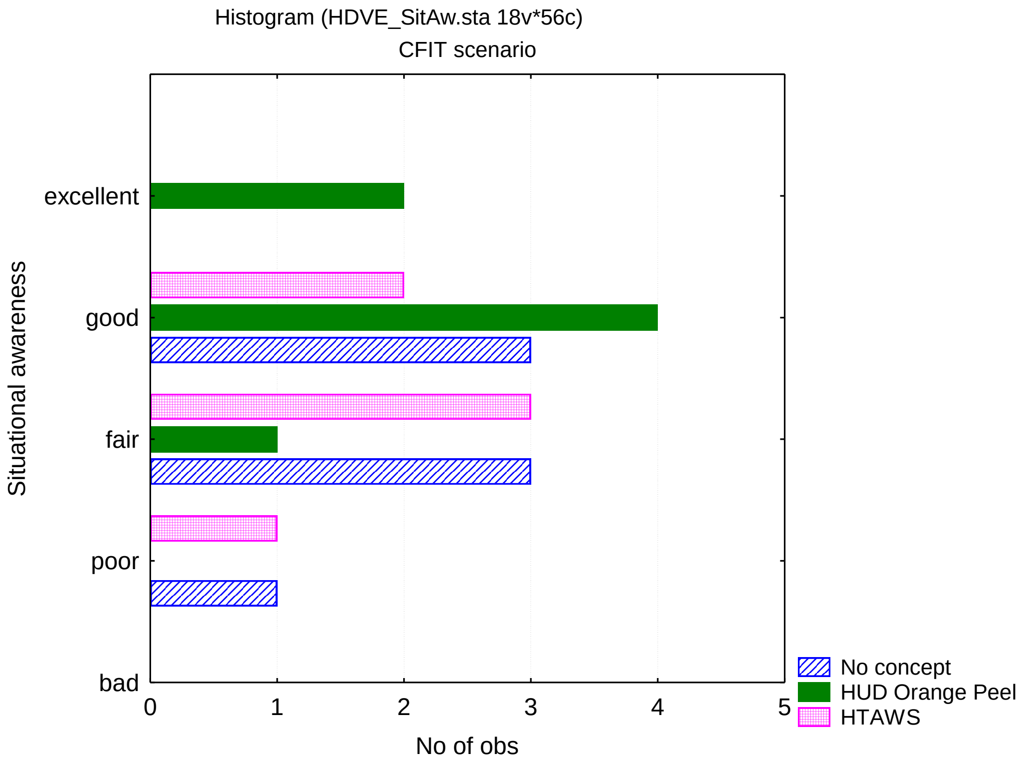


Figure 25 Situational awareness per enhancement concept. CFIT scenario

The enhancement concept had a statistically significant effect ($p<0.05$) on the situational awareness, which was due to the HUD Orange Peel (HOP) having a statistically (nearly) significantly ($p<0.05$) *better* situational awareness (modal value ‘good’) than with ‘no concept’ (modal value between ‘fair’ and ‘good’). Between the HTAWS and the ‘no concept’ there was not much difference.
The major contribution in the HOP with regard to the (improved) situational awareness was the ground bar which indicated height. Although the HTAWS indirectly also gave height-above-ground information (if the alert went off) it did not improve the situational awareness ratings with the pilots.
The few pilot comments on situational awareness that were collected are given in Table 5.

Table 5 Pilot comments on situational awareness with the CFIT scenario

Concept	Comments
HUD orange peel	HTAWS would make it perfect due to look ahead
HTAWS	Rather have visual than aural cues

That is, one pilot flying with the HTAWS commented that for situational awareness he would have preferred a map display (‘visual’) rather than the *audio* alert. This was also the run where a CFIT actually happened (due to an HTAWS-missed alert). Another pilot would have liked to have the HTAWS and HOP combined, noting that the alert information about height from both concepts is different: from the HOP it is the height above terrain, while for the HTAWS it is the time-to-impact or ”look ahead height”.

In the case of the HTAWS for this scenario the alert mechanism was used to good advantage to “skim” the terrain, judging by Figure 26. It was observed during the CFIT runs with the HTAWS that pilots tended to respond quite strongly to the alerts by increasing pitch angle in order to climb and so avoid imminent collision with the ground (hardly any collective inputs were given as the speed was deemed to be high enough). An example of this can be seen in the altitude response on the CFIT scenario in case of the HTAWS. The moment where alerts sounded are indicated in Figure 26.

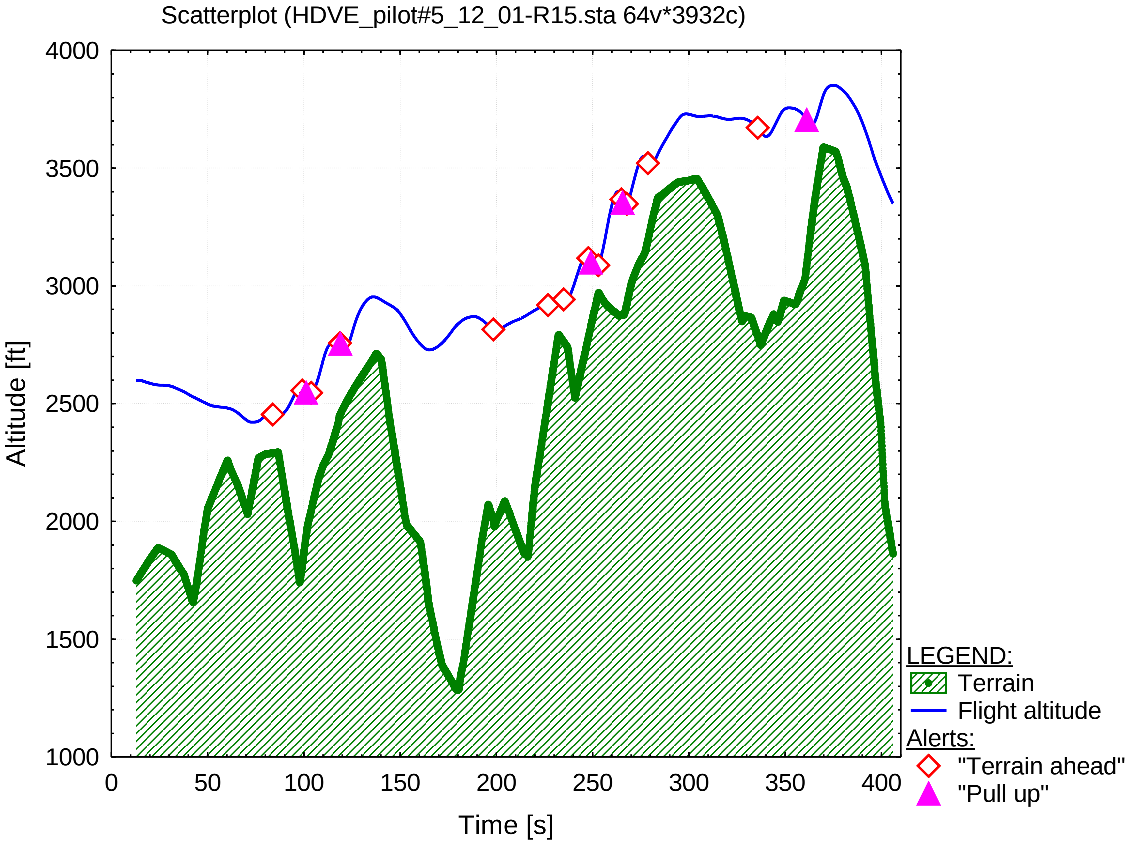


Figure 26 Altitude and alert response during flight with HTAWS in CFIT scenario

Thirteen times there was an alert for terrain ahead, in five cases followed by the “pull up” warning. Sometimes the pilot pulled up more aggressively than at other times, but in all cases of an alert the pilot reacted by increasing pitch angle, as can be seen in the next figure from the same flight.

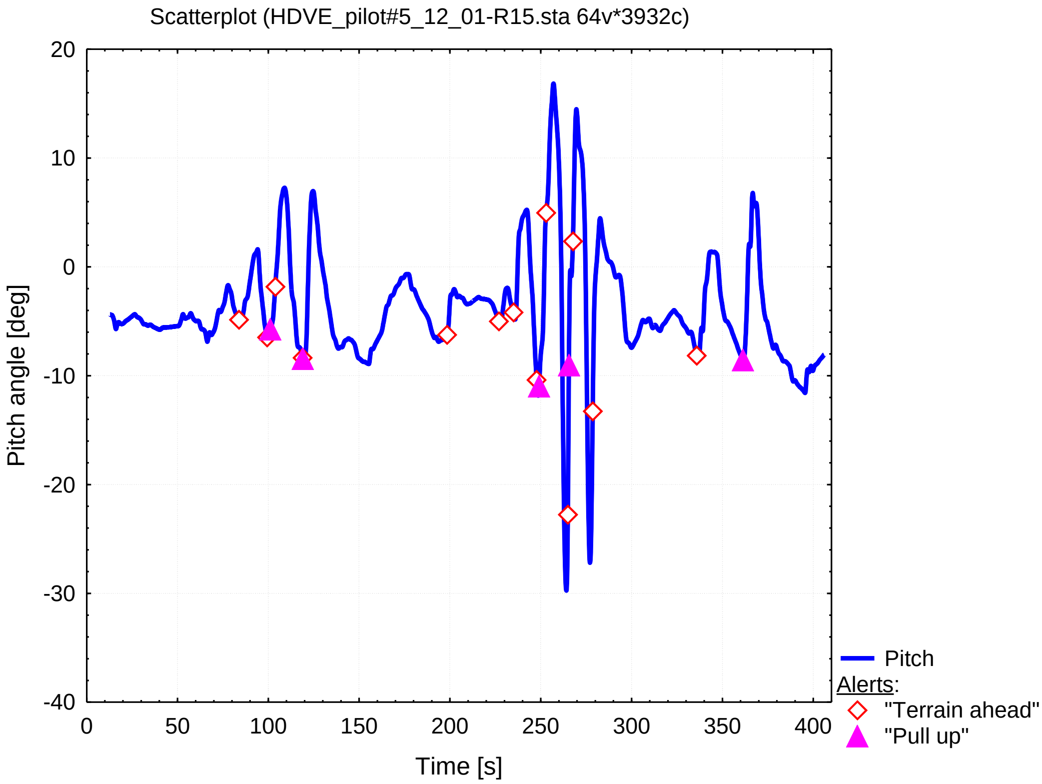


Figure 27 Pitch angle response to the HTAWS alerts during flight of Figure 26

In most cases the pitch angle increased by from 5° to 20° or more due to pilot's action upon the alerts.

The HTAWS concept was very much appreciated. To the question whether one would like to have the HTAWS together with any of the visual enhancement concepts six out of seven pilots stated they wanted the HTAWS to be present with a visual enhancement concept. Which concept they would like the HTAWS to be combined with is indicated in Figure 28 below.

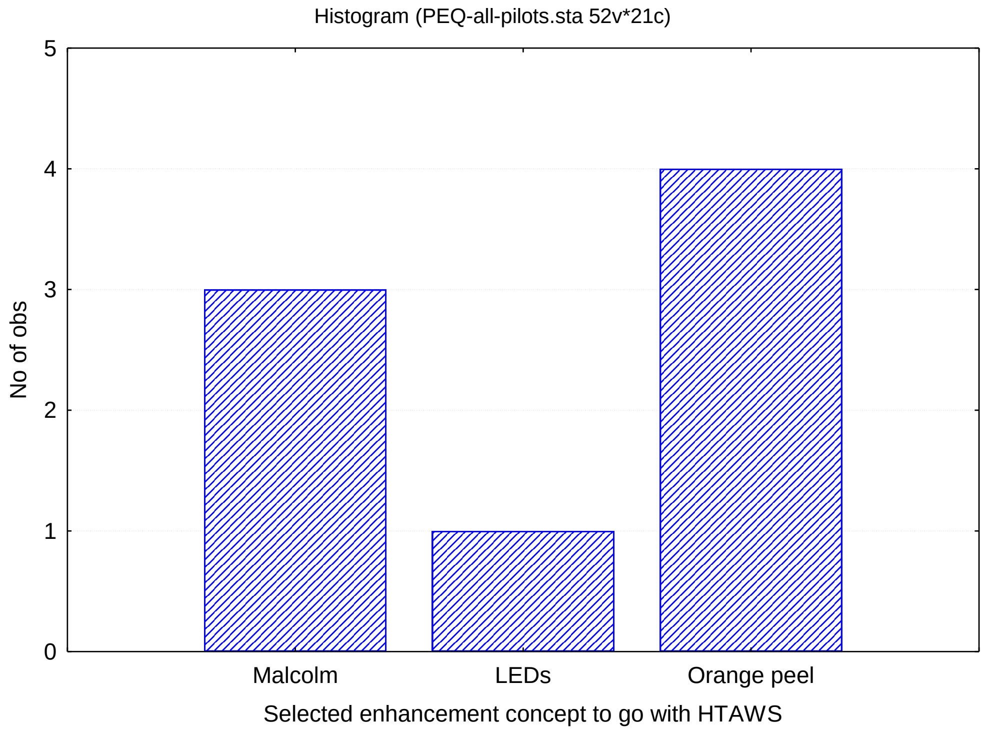


Figure 28 Selection of concepts to go with the HTAWS

Four out of 8 ratings (one pilot gave multiple ratings) selected the HUD orange peel as the visual enhancement concept that should go together with the HTAWS. One pilot even remarked that the HTAWS with the HUD orange peel would be the perfect combination. Another pilot denounced the necessity of the HTAWS in IMC, however, stating that it would make no impact in that case [3)]. A third pilot noted that for VFR flight the presence of an HTAWS should not be mandatory. All the pilot comments collected on the HTAWS concept are given below.

This is the best system for me (combination HUD with HTAWS)
Gives extra important info in bad weather conditions
(Suitable) for CFIT
HTAWS is no help in IIMC conditions
(not needed) because HUD already has height info from the ground bar.

[3)] None of the pilots experienced this situation. It is conceivable that, in the crash cases in the IIMC scenario, the functioning of an HTAWS may at least have had some effect on the pilot's recovery attempt.

6.2.4 Effect of visual/audio enhancement concepts on flight safety

6.2.4.1 Flight risk

A histogram of flight Risk values for the CFIT scenario is given in Figure 29.

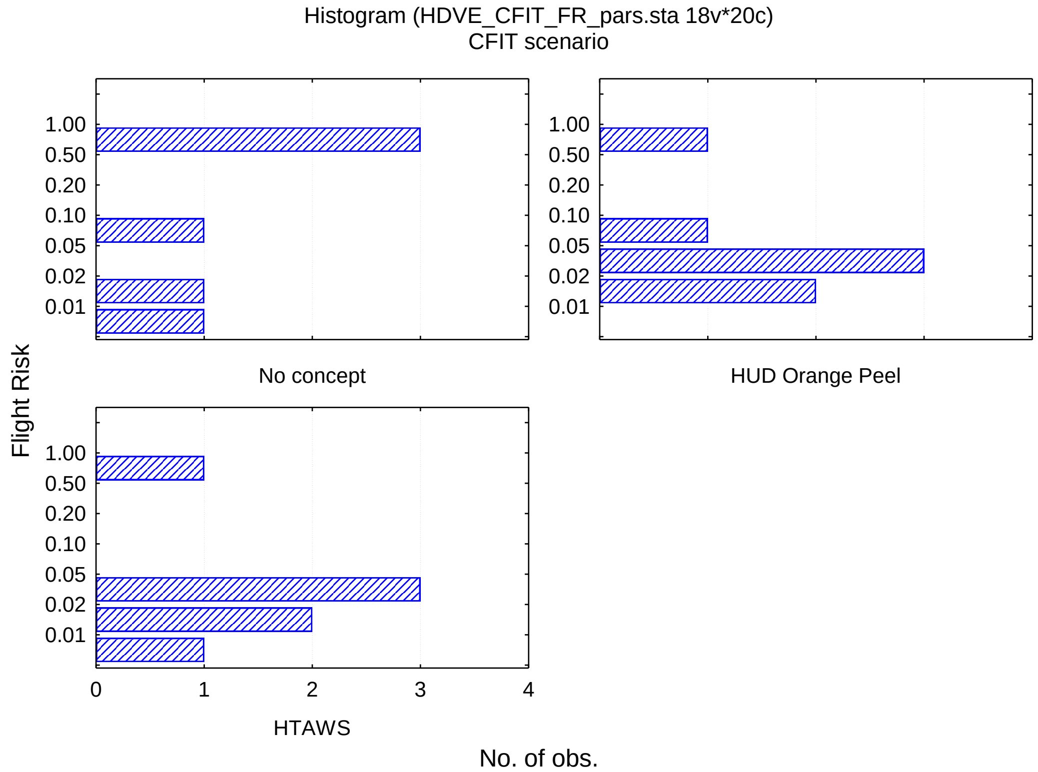


Figure 29 Flight risk values per concept. CFIT scenario

Evident here is that there were 3 crashes with the 'no concept' case, one with the HUD Orange Peel and one with the HTAWS. These are further described in section 6.2.4.3.

Apart from these "outlying" values of 1.0 for Flight Risk, small values less than 0.1 remain with the various concepts This is about an order of magnitude higher than for the IIMC scenario (0.01, see Figure 21). The reason is the contribution to *FR* by the probability of radio height h_R becoming less than zero.

The data for the HOP and the HTAWS look very much alike. There was no statistically significant difference between the concepts.

6.2.4.2 Safety ratings (subjective)

Also a subjective safety rating was given by the pilot in the questionnaire. A histogram of value per enhancement concept is given in Figure 21.

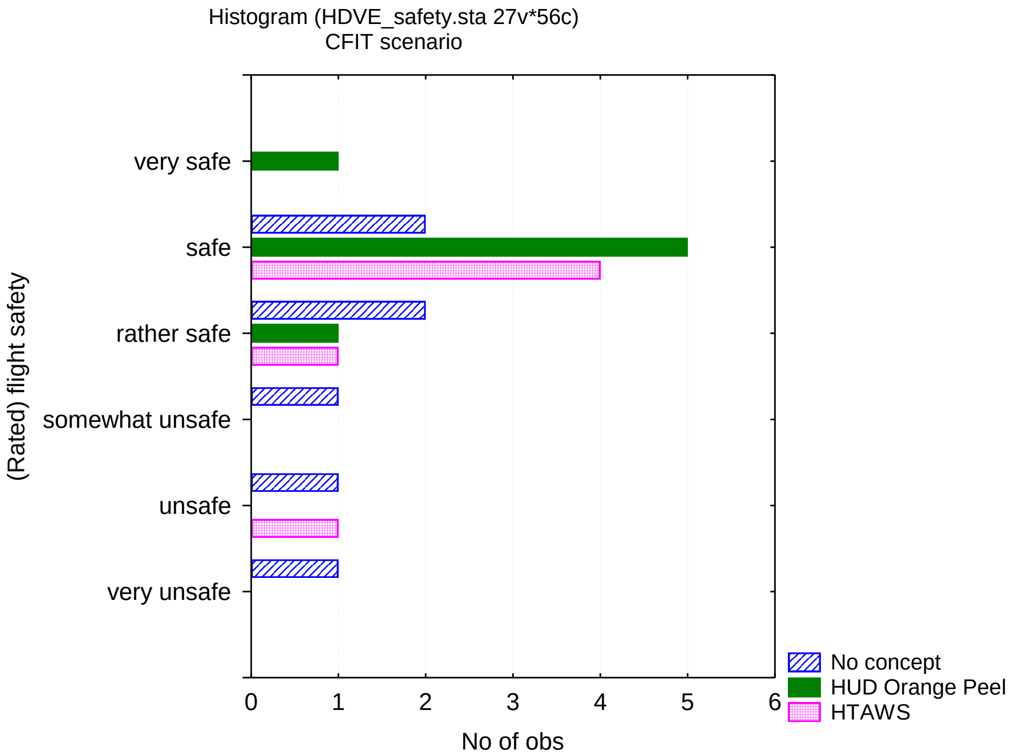


Figure 30 Flight safety per enhancement concept

From the figure it looks as though for the CFIT scenario the HUD Orange Peel had the best safety rating (modal value 'safe').

As it turned out, the enhancement concept had a statistically significant ($p<0.05$) main effect on the rated flight safety, which was due to the HUD Orange Peel (HOP) having been rated significantly safer than the baseline ('no concept'). The feature of inherent "look ahead" in the HTAWS alerts was very assuring to the pilots and well appreciated. Unfortunately with the HTAWS one case of missed alert occurred, which promptly led to a "classic" CFIT: a controlled flight into terrain without the pilot noticing the closeness of the ground. This case was rated as 'unsafe'.

6.2.4.3 Accident rates

A total of 5 crashes occurred on this scenario.

Of the 3 crashes with 'no concept' one was due to a rotor over torque as result of a steep climb out attempt when approaching terrain, which led to rotor rpm loss and then to loss of control, and the other 2 were classic CFITs.

The one crash with the HOP actually went unnoticed by both pilot and simulation crew as it was a "smooth" CFIT, with the aircraft descending from altitude and hitting the downward sloping terrain just past the mountain ridge it was flying over. The one crash with the HTAWS was due to the system missing to give an alert, with a subsequent CFIT.

6.3 Visual Cue Ratings (VCR) and the Usable Cue Environment

For the analysis of the Visual Cue Ratings data from both scenarios were combined. The only concept that featured in both scenarios was the HUD Orange Peel (HOP), while the LED and Malcolm Horizon concepts featured only in the IIMC scenario (the HTAWS featured only in the CFIT scenario but is not a visual enhancement concept). The associated pilot's eye movements have been analyzed in section 6.4.

6.3.1 Visual/audio enhancement concepts and Attitude VCR

Pilot's impressions about the visual cues outside were taken from the so-called 'VCR' ratings for roll pitch, yaw, horizontal rate and vertical rate. The Visual Cue Rating is a rating with a value between 1 (good) to 5 (poor).

As indicated in Ref. [18] the attitude VCR is composed of the roll and pitch VCR by taking the worst of the two, i.e. the following relationship applies:

$$VCR_{attitude} = Max(VCR_{pitch}, VCR_{roll})$$

Although recorded the yaw VCR was not taken into account because the yaw axis did not play a significant role in the performance of the flight.

For the attitude VCR the following results were derived, see Figure 31.

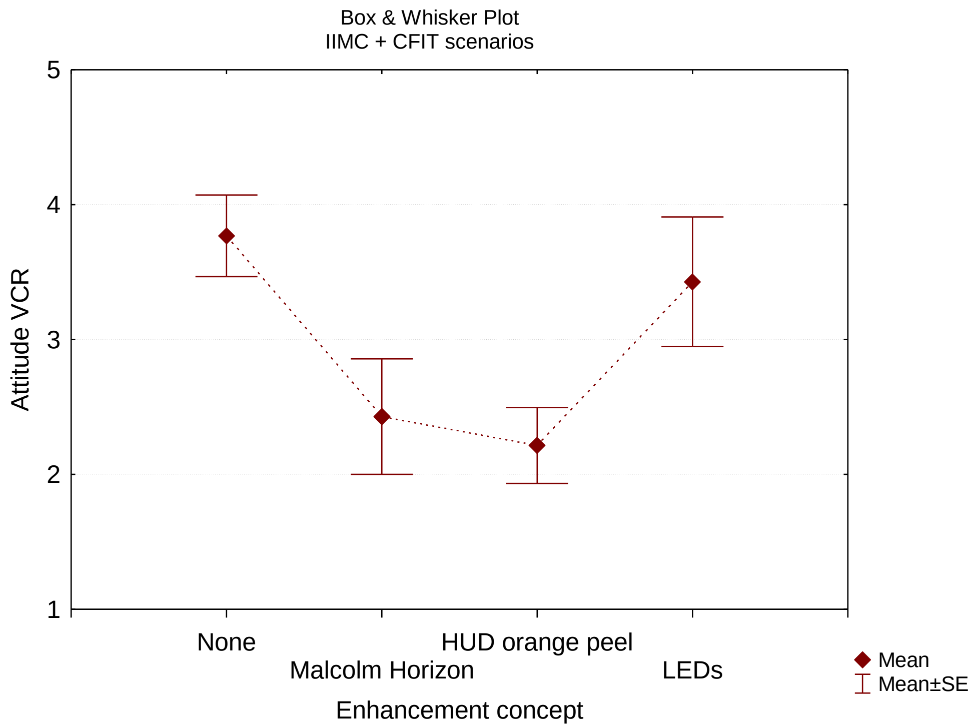


Figure 31 Attitude Visual Cue Rating per enhancement concept (lower is better)

The main effect of the enhancement concept on the attitude VCR was statistically significant ($p<0.05$), mainly because of a statistically weakly significant ($p<0.1$) to highly significant ($p<0.01$) difference from baseline for especially the HUD orange peel, then the Malcolm Horizon and least for the LED concept. With the HUD orange peel quite an improvement in attitude VCR was reached, from about 4 to just above 2.

6.3.2 Visual/audio enhancement concepts and Translational rate VCR

The translational rate VCR was similarly derived by taking the horizontal rate and vertical rate VCRs from the In-Cockpit-Questionnaire into account and by taking the maximum rating per case of the two, i.e. the following relationship applies:

$$VCR_{translational} = Max(VCR_{horizontal}, VCR_{vertical})$$

Results for the translational rate VCR are given in Figure 32.

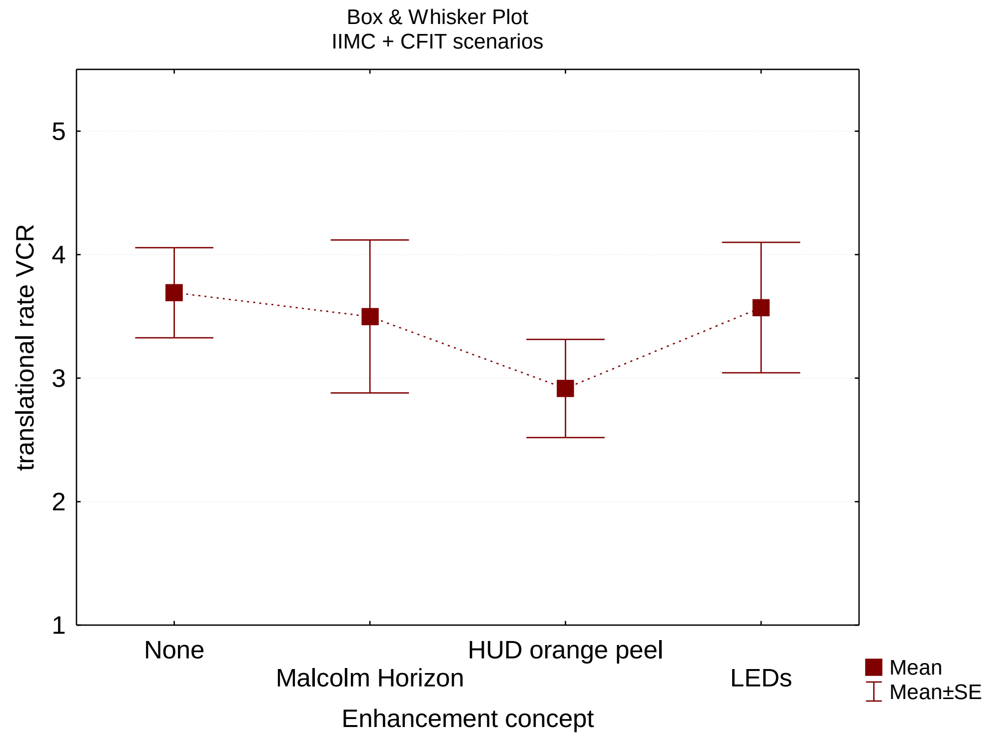


Figure 32 Translational Visual Cue Rating per enhancement concept (lower is better)

There was no statistically significant effect of enhancement concept on the translational rate VCR. The only difference with the baseline came from the HUD Orange Peel, which differed statistically weakly significantly ($p<0.1$), in the sense that it had better translational rate VCRs. This is attributable to the ground bar that would come into view whenever the height-above-ground would become 500 ft or less.

6.3.3 Visual/audio enhancement concepts and Usable Cue Environment

Combined data from the Visual Cue Ratings and averaging per enhancement concept yielded a diagram of attitude VCR versus translational rate VCR as given in Figure 33. Together these VCRs form the Usable Cue Environment (UCE), as also defined in the military rotorcraft's handling qualities specification document ADS-33E (Ref. [8]).

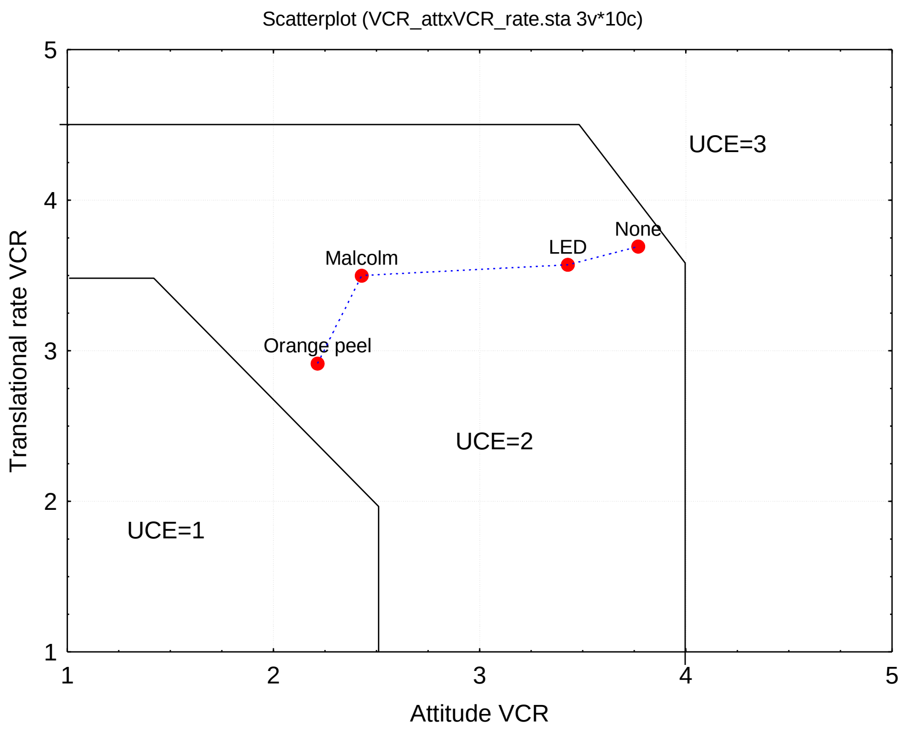


Figure 33 Translational versus attitude VCR of enhancement concepts

Although in fact each point in the figure represents some form of ellipse of scattered data, the mean values given here are quite revealing.

It is evident that the LED concept hardly improved the Usable Cue Environment relative to the baseline case ('None'). The Malcolm Horizon provided a major improvement relative to the baseline and the LEDs, by moving the UCE from the level 2/3 boundary to the middle of the 1/2 and 2/3 boundary, mostly along a constant translational rate VCR line to attitude VCR=2.5. This is still not enough for unaided flight. It is the HUD orange peel which further improved the UCE from the position of the Malcolm Horizon towards the boundary of UCE = 1/2, by mostly improving the translational rate VCR, thanks to the improved vertical rate cue coming from the (red) ground bar. This is a major improvement compared to the baseline case. Formally UCE=1 has not been reached with this concept (yet).

6.4 Eye movement data

Eye movement data are given in terms of focal attention to the areas defined in section 4.7. Because of data quality issues only eye tracking data of 5 out of 6 pilots was usable for further analysis.

6.4.1 IIMC scenario

The IIMC scenarios started with VMC segment followed by IMC segment. During the VMC segment the pilot will generally use the cues from the outside world together with the information displayed on the instruments. In the IMC segment these outside cues have disappeared mostly, with a partial replacement by a visual enhancement concept, so a change in focal attention is expected. In the baseline scenario (i.e. no enhancement concept) the pilot has to use information displayed on the instrument panel. In the other scenarios information given by the visual enhancements concept is also available on the ”outside world”.

6.4.1.1 Malcolm Horizon compared to baseline

In Figure 34 the Malcolm Horizon is compared against the baseline (i.e. ‘no concept’) for both flight segments (i.e. VMC and IMC) of the IIMC scenario. So this is a two-way comparison: IMC versus VMC and Malcolm Horizon versus Baseline.

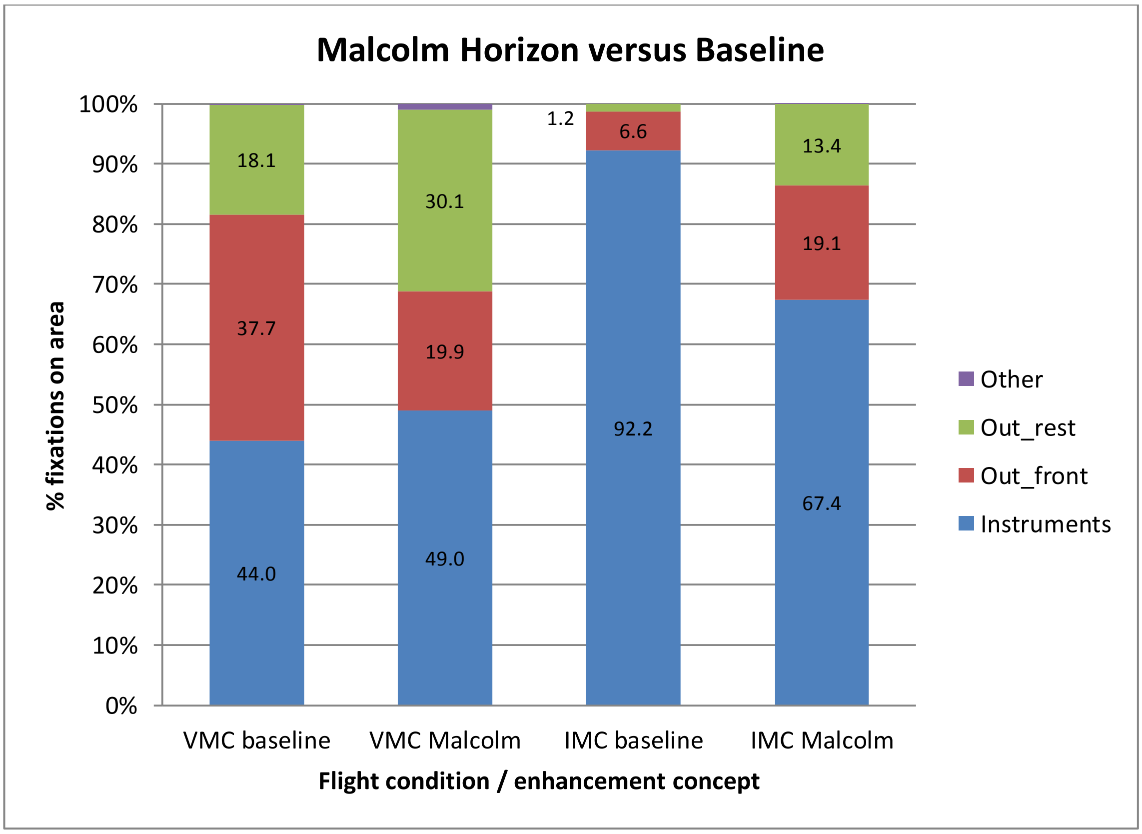


Figure 34 Malcolm Horizon versus Baseline focal attention

The main observations from Figure 34 are:

- In the baseline configuration (without visual enhancement) the pilots divided their attention between their instruments (44%) and looking outside (areas 'Out_front' and 'Out_rest') with a focus on the area 'Out_front' (37.7%). During the experimental runs there is almost no attention on other areas.
- In the VMC segment the Malcolm Horizon concept shows an increase of focal attention on 'Out_rest' at the expense of 'Out_front'
- With the Malcolm Horizon concept there was a change in focal attention between VMC and IMC condition. The focal attention on 'Out_front' remained almost the same, but there was an increase in focal attention on the instruments at the expense of the attention on the areas 'Out_rest'.
- The increase in focal attention on the instruments in IMC was less than the increase observed with the baseline concept. More time was spent looking at the Malcolm Horizon 'outside'. For non-IFR rated pilots this is as expected.

In VMC an increase in focal attention on 'Out_rest' was observed and explained by the focal attention on the left and right side of the Malcolm horizon. In IMC an increase in attention on the instruments was observed but the pilots were looking more outside than with the baseline concept. The assumption is that, compared to the baseline, pilots are paying less attention to the (inside) instrument panel as vital information is available via the Malcolm horizon. In VMC the roll angle information was obtained by looking at the left and right side of the Malcolm horizon. It is expected, as visual workload increases in IMC, that this information is obtained via the peripheral vision, and a reduction in focal attention on "Out_rest" is acceptable.

6.4.1.2 HUD Orange Peel compared to baseline

In Figure 35 a comparison between the HUD Orange Peel and the baseline focal attention is given.

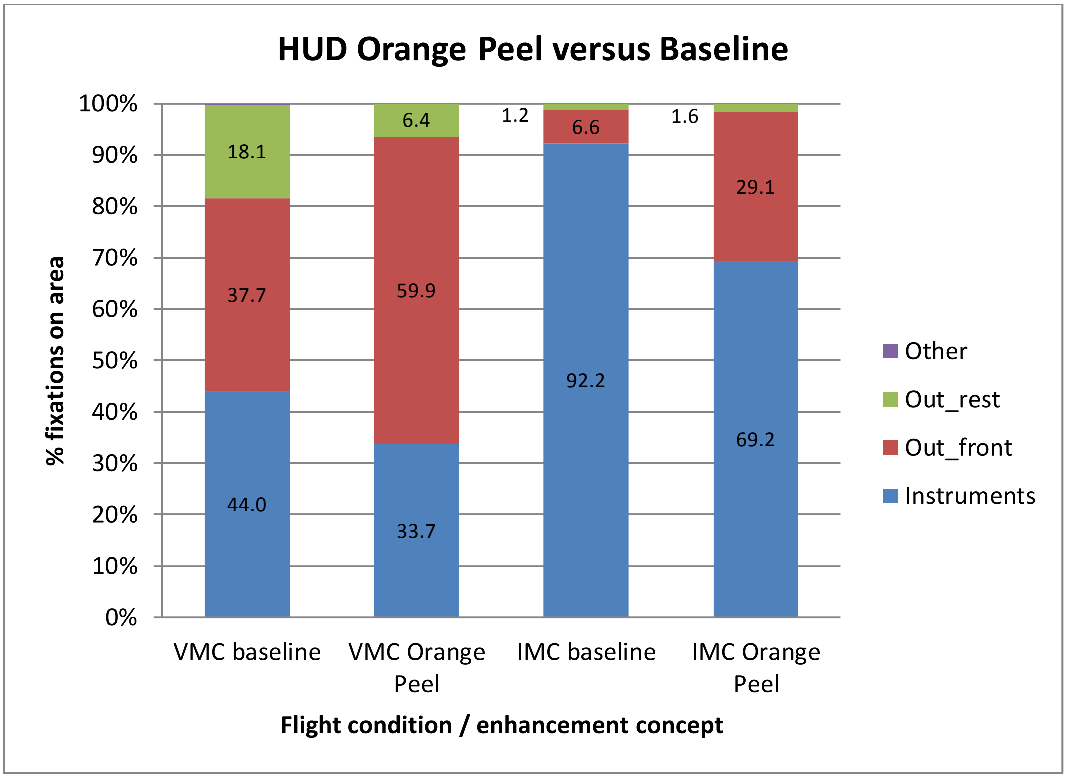


Figure 35 HUD Orange Peel versus baseline comparison (IIMS scenario)

The main observations from Figure 35 are:

- In the VMC segment the HUD Orange concept shows an increase of focal attention on area ‘Out_front’ increased, at the expense of the attention on the areas ‘Out_rest’ and ‘Instruments’, i.e. pilots were looking more at the HUD Orange Peel than at other features outside
- With the HUD Orange Peel concept there was a change in focal attention between VMC and IMC. The focal attention on the instruments increased but less than with the baseline concept. The focal attention on ‘Out_front’ decreased to 29.1% in IMC.
- As with the baseline concept there was almost no focal attention on ‘Outside’ in IMC, just on the HOP (30%) and the instruments (70%).

With the HUD Orange Peel pilots looked outside more, as vital information, normally displayed on the instrument panel was available in the HUD Orange Peel. In IMC, looking outside increased from 7.8% to 30.7%, the increase having been caused by looking on the area ‘Out_front’ where the HUD Orange Peel is displayed. It is assumed the HUD Orange Peel was used to obtain information normally derived from the instruments. The instruments were still used (70% of the time) to obtain all the information needed for performing their task.

6.4.1.3 LED concept compared to baseline

The results of comparing the LED concept against the baseline are given in Figure 36.

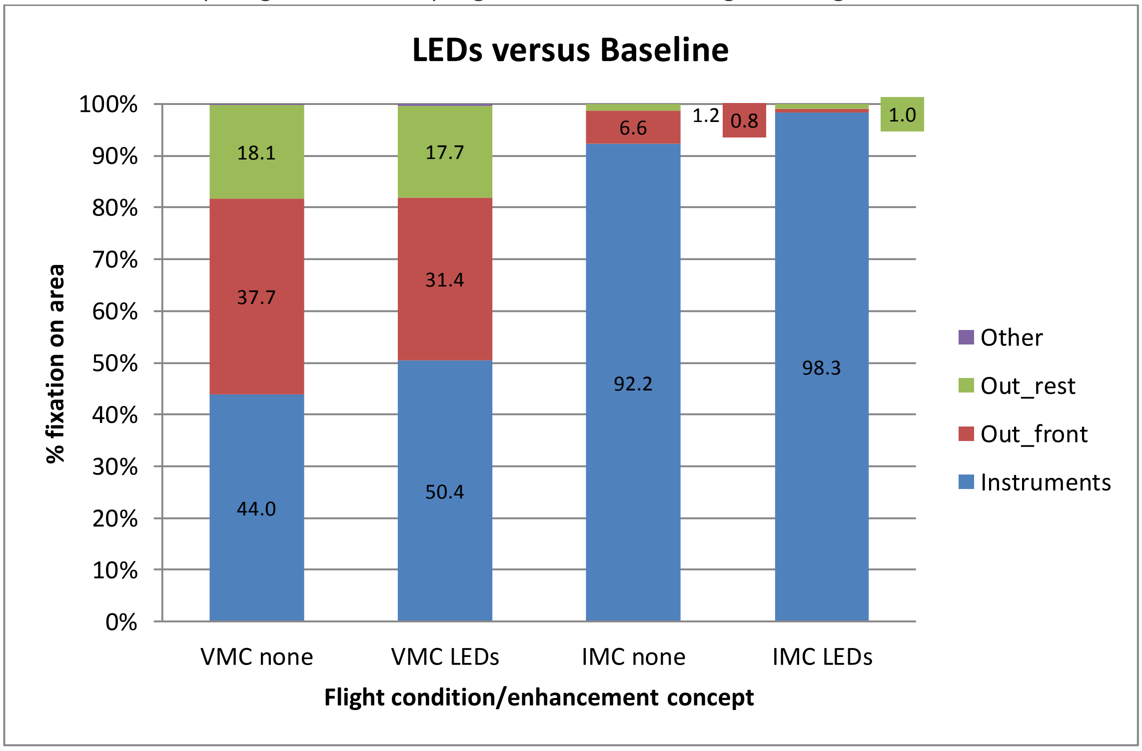


Figure 36 LEDs versus Baseline comparison – IIMC scenario.

The main observations from Figure 36 are:

- In the VMC segment the LEDs concept shows an increase of focal attention on the instruments at the expense of ‘Out_front’
- With the LED concept in VMC pilots spent 6% more time watching their instruments than with the baseline concept, at the expense of attention on the area ‘Out_front’. In IMC the same increase could be observed. In this condition time spent looking ‘Out_rest’ decreased to less than 2%.

The measurement system measures the point of view the pilot is looking at, so it measures the center of the gaze. Information of the LEDs can be detected by peripheral vision. Using the LED visual enhancement concept, an increase in looking ‘Out_front’ was expected as the pilot could use information presented by the LEDs while looking outside. This would result in a decreased focal attention on the instruments. The results do not indicate this effect but indicated rather the opposite. In both flight conditions the focal attention on the instruments increased by 6%. This effect cannot be explained by an outlier in the measurements.

The information of the LEDs will also be detected by the peripheral vision when looking at the instruments. One explanation, especially for the VMC condition, might be that information normally found by looking outside, like roll angle, is provided by the LEDs (in IMC almost no visual

cues outside were available). Another explanation might be that the pilot is cross-checking the information from the LEDs with the instruments.
The visual enhancements provided by the HUD Orange Peel and Malcolm Horizon concepts made the pilots look more outside in IMC (curiosity?). With the Malcolm Horizon more time was spent outside searching for information, with the HUD Orange Peel the pilot was focusing more in the flight direction ('Out_front').

Summarizing the focal attention data for the IIMC scenario the following results are obtained, as given in Figure 37:

- The visual enhancement concepts drew more focal attention out front, and less on the instrument panel, except with the LED concept. This is as expected
- With the Malcolm Horizon also more attention was drawn to 'Out_rest', i.e. more outside but not in front of the pilot. This implies the pilot is also looking at the extremities of the MH line, which is also as expected
- With the LED concept practically no focal attention is given to the outside world, and almost complete focus is on the instrument panel, even more than with no concept, except a very small portion outside (1%) or out front (0.8%). Apparently pilots found nothing outside to look at with the LED concept, which is true. It is possible that the very small amount of focus outside could be related to the pilot looking at the front LED strip that was just behind the instrument panel (see Figure 14).

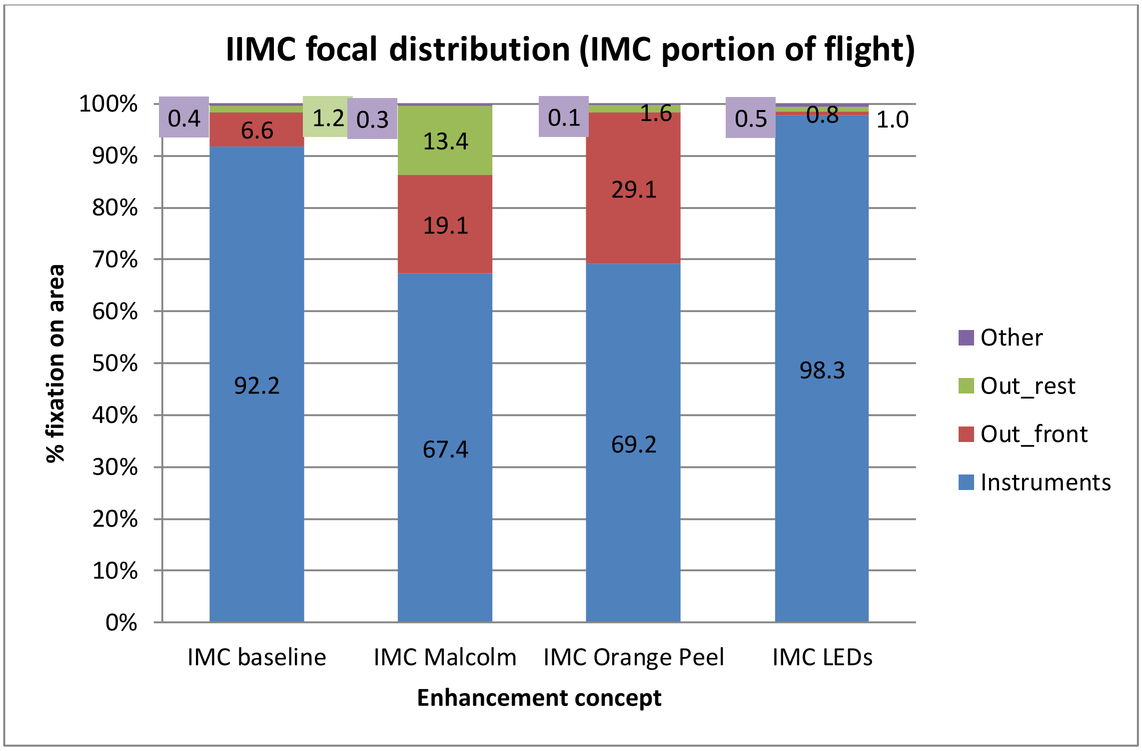


Figure 37 IIMC scenario summary of focal distribution of concepts (IMC segment of flight)

In the previous figures (Figure 34 -Figure 37) the focal attention per area as percentage of time was given. But it gives no information *how often* the pilot changed from looking at one area to another area. These transitions are needed to combine the information available on different areas, for instance cross checking instruments with outside. Figure 38 shows per enhancement concept, in the IIMC scenario, the percentage of transitions to another area, as percentage of the total number of fixations on all areas.

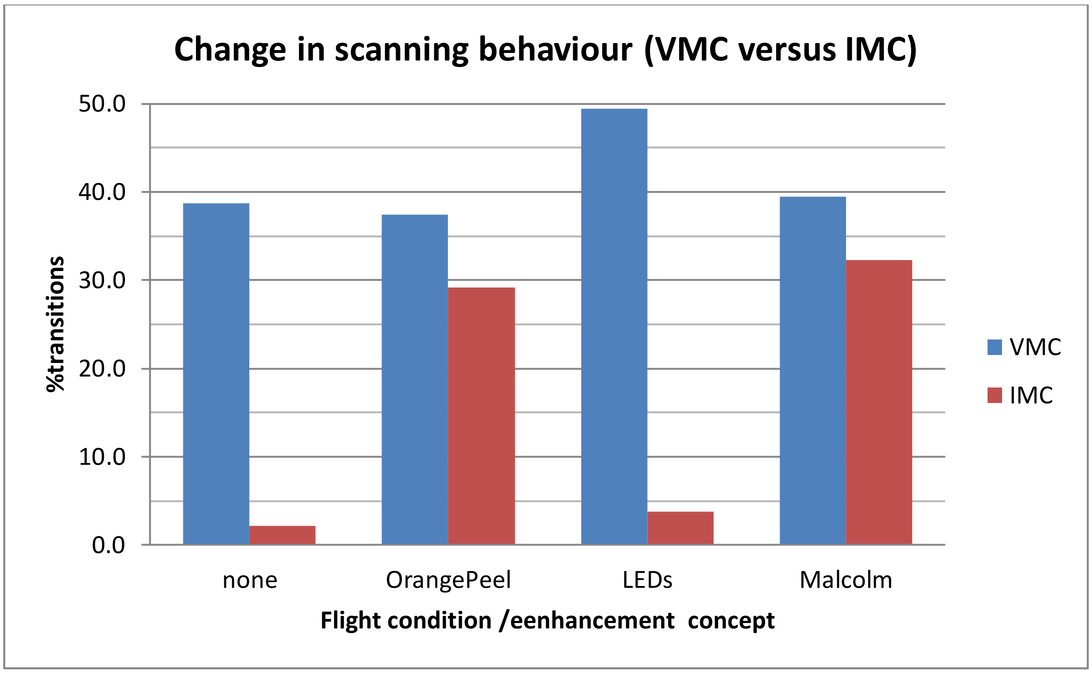


Figure 38 Change in scanning behaviour between VMC and IMC (IIMC scenario)

The percentage of transitions is related to the number of areas looked at and the focal distribution between areas. A pilot looking at just one area will have all fixations on the same area and will make no transitions, resulting in a transition percentage of 0%. A pilot looking at consecutive areas continuously will have a percentage of 100%. If one of the areas has a very low focal attention a drop in transitions is expected.

The main observations from Figure 38 are:

- The LED concept in the VMC condition resulted in more transitions, similar to the baseline. The pilots' eyes are "wandering about" from area to area.
- Going from VMC to IMC with the baseline and LED concepts gave a large decrease in the number of transitions. This is due to the strong focus on mostly one area, viz. 'instruments' (see Figure 37).
- With the Malcolm Horizon there hardly is any difference between VMC and IMC. Looking patterns apparently are the same, as the pilot need not get information from different area in IMC than in VMC.

Based on the distribution in focal attention in IMC more transitions were expected for the baseline concept than for the LED concept. The figure shows fewer transitions, so less cross checking between outside and the instrument panel than expected.

6.4.2 CFIT scenario

The meteorological conditions in the CFIT scenarios did not change and the whole run, from start until end of run (or crash) has been processed and analyzed as one interval.

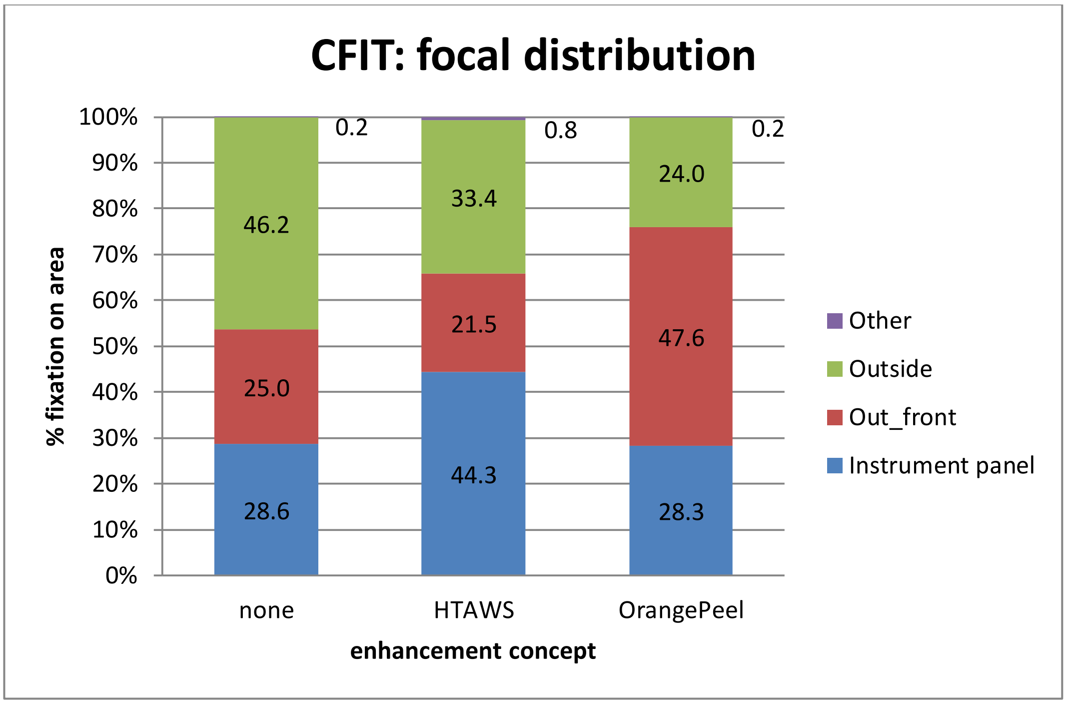


Figure 39 Focal distribution in the CFIT scenario for the enhancement concepts

The main observations from Figure 39 are:

- The time spent on the instrument panel for the HUD Orange Peel concept and baseline were the same (28%).
- With the HTAWS concept more time was spent on the instrument panel (41.3%) than with no concept (28.6%), at the expense of looking outside beyond the front region (33.4% instead of 46.2%).Why this was so cannot be explained, because the HTAWS was expected to show the same visual behaviour as the baseline. Apparently the presence of a “guardian angel” (HTAWS) reduced the need for scanning more outside for possible terrain or related obstacles. As one pilot put it, “*HTAWS is very confidence building*”.
- With the HUD Orange Peel more time was spent on the area ‘Out_front’, in the baseline case more time was spent on ‘Out_rest’. That is, with no concept pilots looked around widely, while with the HOP they ‘reduced’ their overall outside scan, especially the outer edges, to look more at the HUD Orange Peel symbology This is because the HOP attracts attention but also offers information (e.g. the ground bar with height information) The time spent watching the instrument panel is the same for both ‘no concept’ and the HOP. The reduced amount of scan widely outside with the HOP could be detrimental to safety, but the safety data from section 0 indicates the opposite is true.

7 Key conclusions and recommendations

7.1 Conclusions on effectiveness and feasibility

The conclusions and recommendations drawn are predicated upon the following limitations and conditions:

- The simulator is a fixed-base simulator. The issue of moving versus fixed-base has been subject to debate for a long time, and certainly with devices mounted on the pilot's head, a moving base might be required if helmet-mounted displays (HMD) would have been used. Another associated aspect is the question of vibrations which are not felt

- The subjects (pilots) used were not experimental test pilots who have been trained to express aircraft peculiarities in proper terms that are understood by a non-pilot engineer.

- All of the enhancement concepts have been mimicked and not truly built physically. Issues like distorted view due to window curvature and multiple reflections, for example, did not play a role.

- Only day-time conditions were considered. NLR's helicopter simulator has no problem whatsoever simulating night scenes including moon shine, etc., but the operational effect of cockpit lighting and the functioning of the visual enhancement concepts, false reflections, etc. have not been considered.

- The eye tracking data is based only on that of 5 pilots, so in fact most of the findings related to focal attention are more indications or trends than hard facts.

Based on the above limitations and conditions, the following conclusions, in random order, can be drawn:

1. The applied methodology worked well. Giving all pilots the same series of enhancement concepts was no problem. With the scope of tests it turned out possible to perform the experiment within half a day per pilot. For the statistical tests it was thought that 6 pilots would be enough, but this led to sometimes wide scatter in results (e.g. the situational awareness ratings, pilot workload). Partly this is due to the flight-operational background of this group of pilots being less homogeneous than if they had been experimental test pilots.

2. From eye tracker data it appeared that pilots did sometimes not look at all at the concept's display, because they focused only on the ADI on the instrument panel when trying to "escape" the inadvertent IMC condition. The presence of the ADI was therefore paramount to not losing control in IMC. In all the extra flight cases where the ADI had been removed, without an enhancement concept or with the LED concept the flight ended in loss of control.

3. The HUD Orange Peel (HOP) is the best visual enhancement concept tested, in terms of Usable Cue Environment:
   - The UCE improved significantly from UCE~3 to nearly UCE =1, compared to the baseline. UCE=1 has not yet been achieved but is felt to be within reach with minor modifications.
   - The HOP is based on pitch angle, whereas the experimental F-16 HUD orange peels were based on flight path angle. Implementing flight path angle instead of pitch angle would remove the requirement for a reference pitch indication in the orange peel. However, with rotorcraft it is possible, in cases of low flight speeds and high rates of descent, bordering on the vortex-ring state condition for example, that the fuselage angle of attack becomes so large, even negative, that the orange peel indication will become erroneous, i.e. give the wrong cue for recovery. Furthermore, using flight path angle instead of pitch angle would introduce an additional delay in the visual cues-pilot-control loop, making the system even more prone to PIO. The conclusion is therefore that a HOP based on pitch is adequate.
   - The ground bar to indicate height made the HOP almost reach the UCE=1 condition because of the vertical translational cues provided by this bar. Its presence was also highly appreciated by the pilots.
   - The test pilot's rated handling qualities, compared to the baseline, deteriorated due to PIO, as also confirmed by another participating pilot (so 2 out of 7 pilots reported a PIO issue). It is felt, however, that the concept has potential to improve the Level 2 handling qualities of the R44 to Level 1 if corrected for this PIO tendency, see the recommendations.
   - For training the pilots more time was needed than for the second-best concept, the Malcolm Horizon, where the line corresponds directly with the outside horizon. With the HOP this is not the case.
   - It was found from the eye tracker data that the HUD Orange Peel (HOP) in the CFIT scenario attracted focal attention of the pilot at the expense of looking more around outside. Unless the HOP delivers more information this could have a

detrimental effect on safety, although subjectively the HOP was rated 'significantly' safer than no concept, where the pilot did look more around outside. In a scenario with other traffic besides mountains this drawing attention away may have a detrimental effect on safety.

4. The Malcolm Horizon was the second best visual enhancement concept in terms of Usable Cue Environment. It was simple to interpret and pilots were quick to understand what the line meant:
    - The handling qualities ratings improved, from the rotorcraft's original Level 2 to Level 1.
    - The Line indication may become ambiguous in case bank angle exceeds 90° so it is not suitable for unusual attitudes when or if they occur.
    - With the MH pilots spent about 20% less time than with no concept watching the instruments, but spent this time watching in front and further outside more, as expected.

5. The HTAWS audio concept was greatly appreciated:
    - HTAWS comments were very favourable. The Time-To-Impact that was used as a threshold was much appreciated by the pilots as a simple concept.
    - It missed giving an alert only once.
    - The eye tracking data showed that with the HTAWS more time was spent looking at the instruments than with no concept in the CFIT scenario, at the expense of looking widely outside. Apparently the system is such a "confidence builder" that pilots felt it was not necessary to look for terrain that much since they had the "guardian angel" (HTAWS) on board.

6. The LED concept in general is quite an elegant concept and relatively cheap to manufacture compared to the other visual enhancement concepts and quite flexible in use by the many different programming of the motion of individual lights, colours, etc. that can be applied. It has the advantage that it does not depend on reflecting surfaces in the cockpit, such as curved windows for example. But the following points can be made:
    - The LED concept as implemented, i.e. with "static" lights indicating roll angle, etc., should be regarded as not suitable for application. The working of peripheral cues

did not materialize in the way it had been expected. Considering the technological readiness level of this concept (TRL =3-4) this is no surprise. There are, however, more ways to set up/define the peripheral cueing to improve the situation.

- The vertical rate-of-descent cues were appreciated.
- With the LED strips lighted up so they indicate the attitude this could make the concept sensitive to the human size because of the eye reference position. This makes a general application more difficult.
- Because of the physical nature of the concept, i.e. mechanical strips attached to doorposts, etc., the ingress into or egress out of the cockpit could carry the risk of damaging or bending the LED strips and having mechanical strips attached left, right and in front of the pilot, it is possible when leaving or entering the cockpit that the pilot may physically touch, dislocate.
- When flying in IMC with the IIMC scenario pilots did not look outside but focused almost completely on the instrument panel, even more than with no concept. It is not clear to what extent the peripheral cueing will then impact the pilot's performance on a subconscious level.

7. Technically speaking all the concepts evaluated are feasible using additional (miniaturized) sensors such as an augmented GPS (i.e. a GS augmented with a Satellite-Based Augmentation System, SBAS), AHRS and a terrain database. This type of equipment is already available or becoming available very soon (e.g. "electronic cockpit"). The least complicated concept is probably the LED concept (no reflective windows needed, simple LED strips to be mounted in the cockpit, flexible light sequencing through programming), whereas the HUD Orange Peel requires an image generator, projector and reflecting glass or (flat) window to reflect the imagery. The Malcolm Horizon requires a programmable scanning laser within a structure and computer for programming the orientation of the line.

8. Lessons learned from the experiment were among others:
   - Finding a suitable visual scenery for especially the CFIT scenario was quite a challenge. The scenery had to be realistic even while pilots knew beforehand there was likely going to be a CFIT condition, making them even more alert. In the end the pilots rated all two scenarios as (very) realistic. One pilot, with some mountain flying experience, really appreciated the CFIT scenario in that he found it looked very

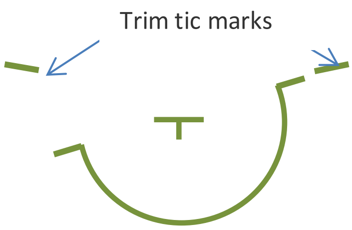
realistic especially with regard to the translational cues that were visible when passing over mountain ridges.

- The presently used group of 6 non-experimental test pilots may be too small to obtain statistically significant results with, certainly with a widely varying background and flight experience. It was necessary, however, to have such pilots as subjects since the accidents upon which this study was based occurred exactly within this group. It is difficult to say how many more pilots will be needed, but with data drop out risks included a doubling of the number could be in order.

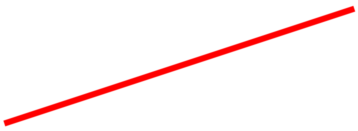
7.2 Recommendations on effectiveness and feasibility

In the light of the conclusions drawn, the following recommendations can be made:

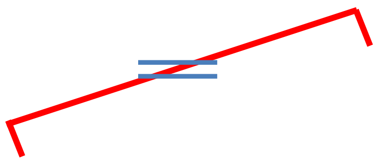
1. A pitch reference could be added especially to the HUD Orange Peel and, to a lesser extent, to the Malcolm Horizon. The alternative is more learning time for the pilot (in practice), as it takes time to become familiar with the rotorcraft's pitch attitudes for various conditions of trim. A simple way of doing it for the HOP is by adding a few tic marks, as shown below.



The present Malcolm Horizon indication becomes ambiguous when the bank angle increases beyond ±90°. Taking the test pilot's remark into account about having a reference pitch indication, an improved MH might look as sketched below.



a) Original Malcolm Horizon



b) improved Malcolm Horizon with pitch reference

There is a short (double) reference line, which can be set using a trim button; the line itself has downward stubs or "wings" at the end to indicate which way is down (to earth), to avoid the ambiguity issue.

2. It is felt that the usable cue environment reached with the Malcolm Horizon or HUD Orange Peel can be further improved to reach UCE=1. It is recommended to perform these developments by relatively minor improvements in the display layout, functional design, etc.

3. The HUD Orange Peel should be improved to alleviate PIO. The way to cure the PIO tendency is to reduce the Orange Peel-to-pitch ratio in order to reduce the overall loop gain. In the implementation in this experiment the orange peel would be complete for -30° of pitch. This could be increased to eventually a minimum of -90°. The exact amount can be established after a stability analysis and a limited piloted evaluation.

4. It is recommended to perform tests with the ADI removed from the cockpit to truly test the usefulness of any visual enhancement concept This is because there are R44 versions on the market that do not have an ADI on board.

5. In order to fully evaluate a visual enhancement concept it is recommended to also perform unusual attitude tests.

6. It is recommended to perform tests with a visual enhancement concept combined with an audio enhancement concept (HTAWS). The interesting question of course is whether the audio concept will add to the confusion or not when in unusual attitude, inadvertent IMC, etc.

7. So far only a cruise flight condition had been evaluated owing to the accident statistics. It may be argued that other scenarios are also worthy of investigation. One topic mentioned by one of the (instructor) pilots was the question of dynamic rollover in hover, where he thought these concepts might help in preventing an accident from occurring, steep approaches to oil rigs at night, and other rotorcraft types. The “next” highest level of accident risk from the safety analysis was the obstacle or wire strike accident for Class 1 rotorcraft, after which came the obstacle or wire strike with a low setting sun. The low, blinding sun could eliminate the functioning of the outside visual cues of the MH or HOP, so it is recommended to study the working of the visual enhancement concepts under conditions of low setting, blinding sun, which will be part of the definition of the “nest” scenarios.

8. One clear recommendation is to improve and test the LED concept, e.g. by making the roll attitude cue not a steady-state cue but a moving up/left-down/right or vice-versa cue, i.e. the motion of the peripheral cues moving up/down will give an indication of roll angle, the amount of motion up/down being proportional to the deviation in bank angle. The same can be done in pitch using only the front LED strip. This brings the upgraded LED concept close to what has also been described as the "barber pole" concept, see below.

This concept came out of the first NLR-EASA brainstorming meeting, but was later discarded by NLR on the argument that the LED concept would be quite identical, providing similar cueing as the barber poles would (but, as became evident, apparently this was not the case). This "barber pole" effect also makes the concept insensitive to human size.

9. In order to reduce the risk of loss of situational awareness, in the sense of being unaware of descending too fast, it is recommended to have at least the vertical descent rate cueing that came with the LED concept in the cockpit. It was a great awareness trigger and appreciated by the pilots.

10. All concepts could act as a confidence builder, as was especially seen with the HTAWS concept. When any of these, or other, concepts are implemented it is highly recommended to combine its introduction with an awareness campaign to highlight that the concerning concept is meant as an escape / prevention concept and specifically not to extend the operational limits.

11. As a next step towards cockpit implementation, and so increase the TRL level one step further, it is recommended to include curved cockpit windows (or the effects thereof) in the next series of manned simulations with the Malcolm Horizon especially, and/or HUD Orange Peel to a much lesser extent. This will shed light also on how complex it will be to correct for window-induced distortions, and the extent to which distortions can be allowed. For the evaluation of the upgraded LED concept, however, these curved windows are not required as the LED concept does not depend upon reflecting surfaces. Instead of mechanically providing curved windows in a simulated environment the effect of the curvature can also be computed instead using a program similar to the one that was used to compute the optical field-of-view shown in Figure 11. This would be more feasible than installing curved windows.

12. With any of the follow-on tests it is recommended to have the experimental results verified by an experimental flight test pilot/engineer.

13. As a final recommendation one issue concerns head-mounted displays. It is possible that enhancement concepts could be developed that are applicable to (low cost) Head-Mounted Displays (i.e. simple spectacles with gadgets, etc. instead of advanced helmets). It is recommended to monitor further developments of these devices for possible inclusion in a follow-on experiment.

7.3 Practical steps for implementation

7.3.1 Design

The design of both the Malcolm Horizon and the HUD Orange Peel is not yet complete since additional features need to be added to the displays, as indicated with the recommendations. For the LED concept this applies even more strongly. The MH and HOP concepts have been around in the fixed-wing world for quite some years already, but have not found application yet in the rotary-wing world. Also in the automotive world much work is presently being done in the area of head-up displays, which may carry over to the rotary world. That is why the TRL values for these concepts are from 6 to 8, and even less for the LED concept (estimated TRL=4). To increase this to TRL=6 requires additional piloted simulator tests with the upgraded LED, as recommended in para.7.2.

7.3.2 Certification

Before proving that the concept is “air worthy” the additional tests as recommended need to be carried out before the concepts are ready for airworthiness certification according to CS-27

(Small Rotorcraft). Since the visual and/or aural cueing concepts fall in the non-required category the certification needs to focus on possibly generating misleading information, rather than on fail-safe issues.

For the HUD Orange Peel it must be realized that a double system may have to be installed, for pilot and co-pilot alike, unless a single system can be made that is transferrable from one pilot to the other. With the Malcolm Horizon or the LED visual enhancement concepts a single system will do.

7.3.3 Deployment

Deployment of the concepts depends upon the maturity level and the TRL level they are at. Presently they are not mature enough to be installed already in small rotorcraft, as the recommendations have made clear.

It is important that the regulating authorities do not delay any further needed development work on these concepts, as they are presently entering the “electronic cockpit”. The problem is that most of these advanced features are all head-down displays because they have been developed at the level of the system supplier but not the rotorcraft designer. But, as Figure 5 on page 23 shows, helicopter manufacturers “are on the move” in the development of new, advanced integrated cockpits.

7.3.4 Operations

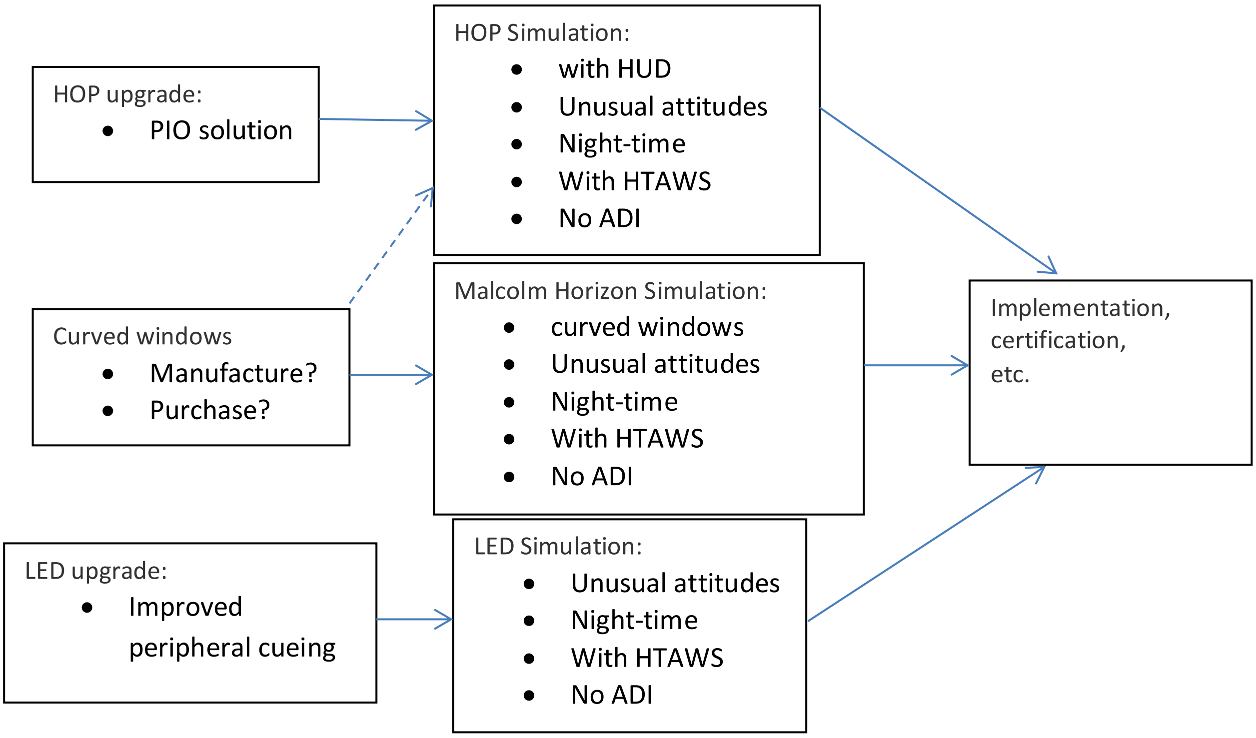
If the operator leaves the visual enhancement concept in the rotorcraft, and active when switching on power for example, it will be easier for pilots to understand and become familiar with the novel visual enhancement concept(s) implemented. The pilots must have been instructed that with this device the rotorcraft will still be certified for VFR use if so equipped before adding the enhancement concept. For the concept(s) to be eligible for night-time use a dimmer switch should be available to adjust the luminance of the displayed information.

7.3.5 Training requirements

For the HUD Orange Peel it is felt that more training is required before the pilot will intuitively act upon the cues given than is the case with the Malcolm Horizon. However, when presenting the display all the time the aircraft is airborne the learning will be substantially reduced. For the LED concept this will certainly be true.

7.3.6 Steps and obstacles to implementation

Below is sketched in rudimentary form what some of the next steps (programs) could be to increase the TRL to the next level for the 3 visual enhancement concepts.



All simulation exercises should be done with more pilots than has hitherto been done.

One major obstacle to implementation could be the operators' (un)willingness to install such a concept in his/her (small) helicopter for rental or lease, owing to the costs involved, unless the installation has been prescribed by the regulatory authorities for safety reasons. Pilots and operators alike need to be convinced that the extra weight, cost, etc., are worth the lives saved one day.

8 Limitations or un-assessed issues

One of the issues that have not been evaluated is the use of the visual enhancement concepts at night. If they are going to be used, the night-time use should also be considered, not only in terms of luminance and colour, but also in terms of secondary reflections, nuisance reflections, etc., and how it will affect the pilot's performance.

As explained elsewhere, the Malcolm Horizon concept was not implemented such that a line was projected into or onto the cockpit, cockpit windows, floor, etc. This is how the original concept was set up. With the projection of the MH on a curved window there will be distortions that will need to be corrected for. The complexity of correcting the scanning laser for this effect would be a next step in the evaluation of the MH. That is why this has been included in the list of recommendations.

Another fairly important issue concerns the vibratory environment in which these concepts should operate. It is possible that the vibrations will outperform the motion of the cues one is looking at, or will cause a blur to occur or damage fragile electronic components.

As evidenced from the recommendations a combination of a visual and an audio enhancement concept has not been evaluated. An important issue here when having both of these systems on board is the synergy of both systems. The audio system, for example, should not add to the confusion in the cockpit when both systems are functioning, or vice-versa. The type(s) of scenarios under which this is to be investigated is uncertain.

9 Acknowledgements

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PH-HBH

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Appendix A Questionnaires

Appendix A.1 In-Cockpit Questionnaire (ICQ)

HDVE evaluation

Pilot’s name:

Date:

Run no.:

Pilot performance

Rate: a) your task *performance* (in DVE)
b) your task *workload* (during DVE)
c) the *characteristics* of the helicopter (model) flown under the present circumstances,
by encircling the appropriate number. For the Cooper-Harper Handing Qualities Rating (HQR) see first the Cooper-Harper Rating scale in the cockpit.
As for the Visual Cue Ratings: if the cues changed (worsened) during the run, rate only the portion of flight with the worst visual cues.

A) TASK PERFORMANCE	Clearly within desired performance limits	Desired performance marginally achievable	Clearly within adequate performance limits	Adequate performance marginally achievable	Adequate performance not achievable
Rating	← 1	2	3	4	5 →

B) TASK WORKLOAD	Low	Moderate	Considerable	Extensive	Intolerable
Rating	← 1	2	3	4	5 →

C) SYSTEM CHARACTERISTICS	Satisfactory	Minor but annoying deficiencies	Moderately objectionable deficiencies	Very objectionable but tolerable deficiencies	Major deficiencies but controllable
Rating	← 1	2	3	4	5 →

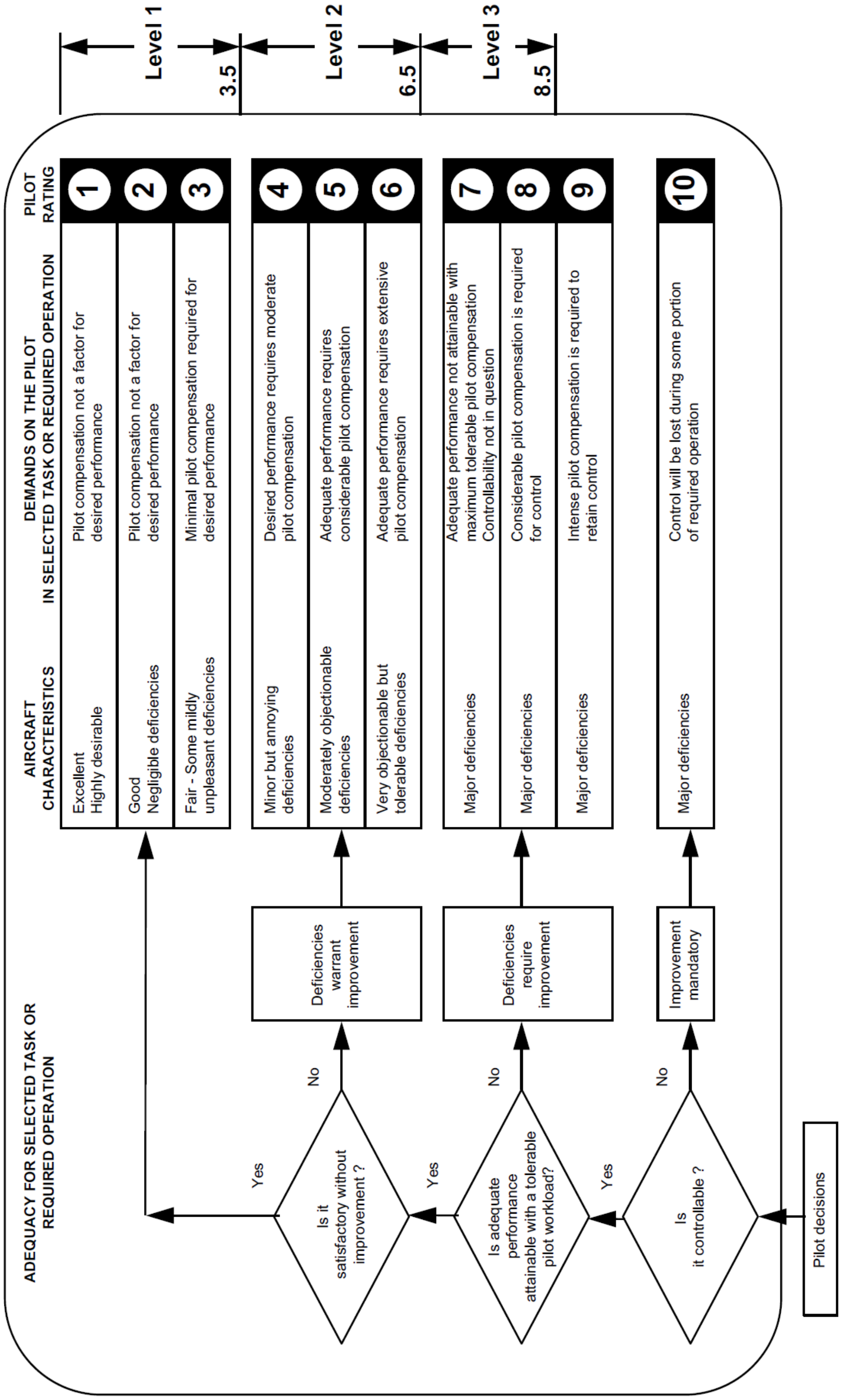
D) Cooper-Harper HQR	1	2	3	4	5	6	7	8	9

E) Visual Cue Ratings (VCRs)

VCR - Roll	Good		Fair		Poor
Rating	← 1	2	3	4	5 →
VCR - Pitch	Good		Fair		Poor
Rating	← 1	2	3	4	5 →
VCR - Yaw	Good		Fair		Poor
Rating	← 1	2	3	4	5 →
VCR - Horizontal rate	Good		Fair		Poor
Rating	← 1	2	3	4	5 →
VCR - Vertical rate	Good		Fair		Poor
Rating	← 1	2	3	4	5 →

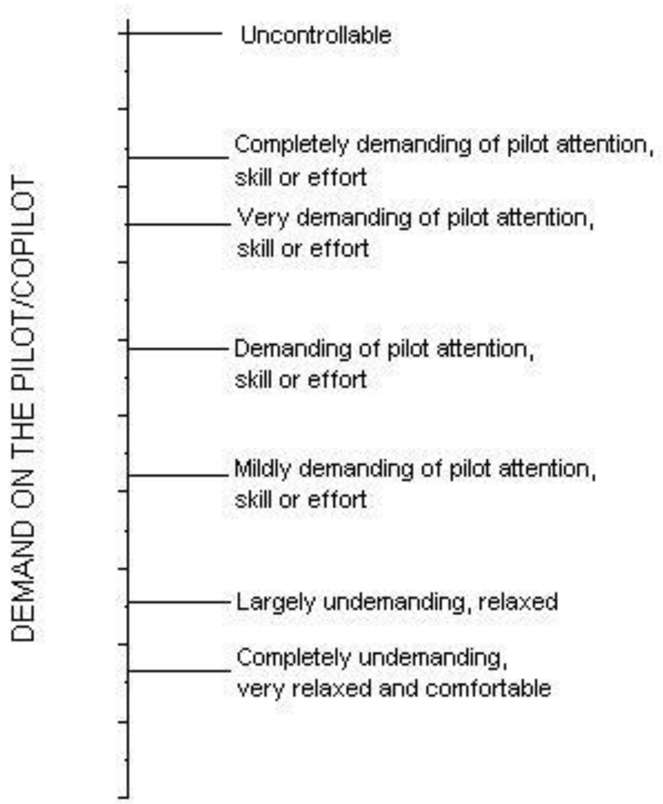
OVERALL COMMENTS

Cooper-Harper rating scale

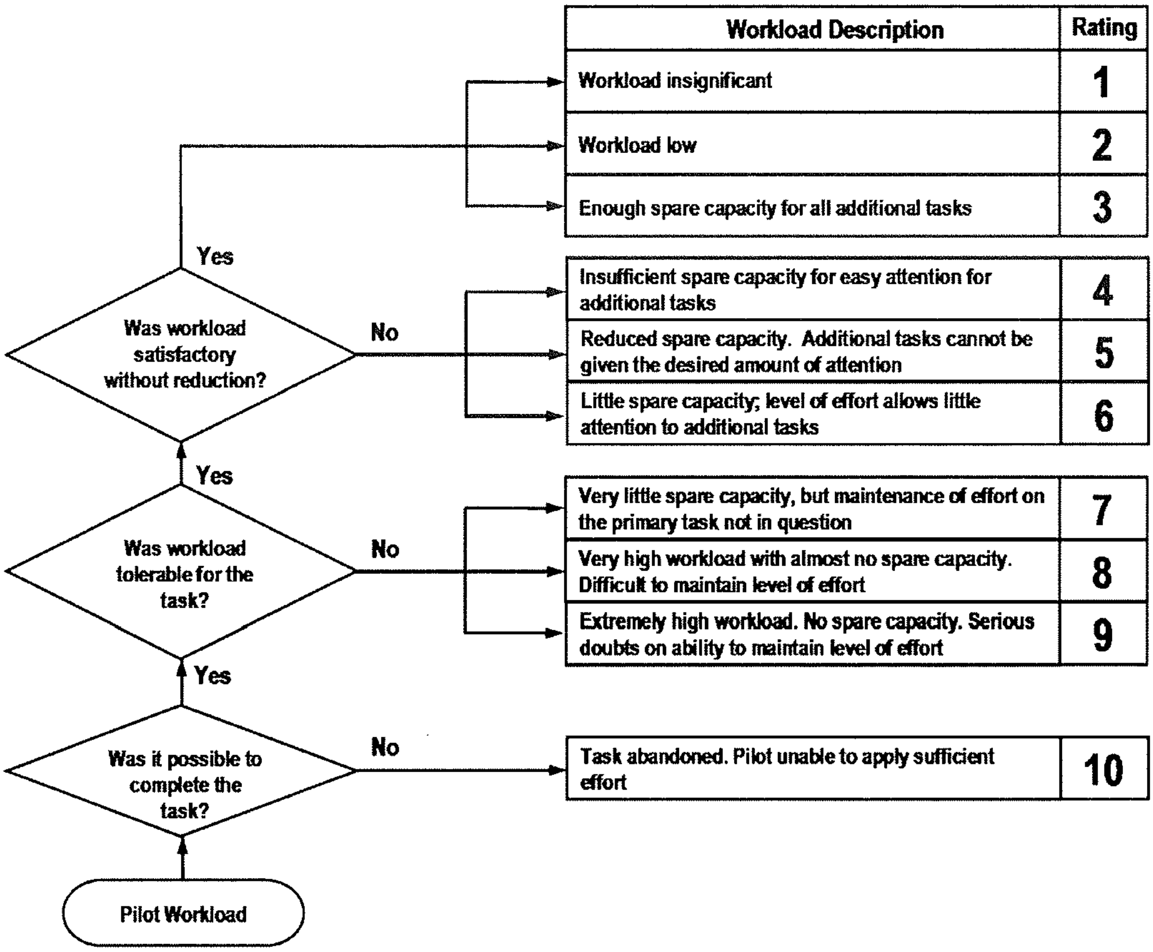


Workload
The pilot's workload will be obtained in two ways, viz. a) by using the continuous, adjectival "DEMAND" scale, developed by McDonnell, and b) by the ordinal BEDFORD rating scale, developed by DERA at Bedford (at the time).

How was your workload during the DVE portion of the flight? Use the "DEMAND ON THE PILOT" scale below by putting a tic mark across the vertical scale at that point where you feel it is most appropriate, watching the adjectives along the scale.



Select a number using the Bedford workload rating (BWR) scale below to indicate your workload.



BWR = ….. (1-10)

Situational awareness

Please indicate below (select only one box) your situational awareness, in terms of awareness of your attitude and proximity to the ground or obstacles, during the DVE portion of this run.

☐ bad ☐ poor ☐ fair ☐ good ☐ excellent

Crash or not

Did you crash during this run? ☐ yes ☐ no

If 'yes', please indicate below why (in your opinion) (use one box only):

- ☐ Unaware of proximity to the ground
- ☐ Lost situational awareness
- ☐ Didn't see the ground timely enough to prevent impact
- ☐ Was distracted too much from observing the ground
- ☐ Lost control during inadvertent IMC
- ☐ Had lost all visual cues needed
- ☐ Other (specify):

Comments:

Acceptance of concept
If an enhancement concept was present, how well do (or don't) you accept/reject this concept for use in the cockpit?

- ☐ fully rejected
- ☐
- ☐ neutral
- ☐
- ☐ fully accepted

If not 'fully accepted', explain why not:

Comments:

Ease of understanding, interpretation of concept
If an enhancement concept was present, how easily did you understand and interpret the indications that came with the concept in following it up, what it meant, etc. (tick only one box)?

- ☐ Very easy

☐ Easy

☐ Somewhat easy

☐ Somewhat difficult

☐ Difficult

☐ Very difficult

Is there information missing?

☐ yes ☐ No

If 'yes', indicate which one by ticking one or more of the boxes below:

☐ No vertical information (i.e. altitude, sink rate)

☐ No ground speed information

☐ No distance to obstacles information

☐ No attitude information

☐ Other (specify):

Compelling/fixating nature of concept

If an enhancement concept was present, how compelling or fixating did you find the visual enhancement concept to be, i.e. does it distract your attention from other tasks or disturb you in any way or fixate your looks?

☐ Very compelling
☐ Compelling
☐ Somewhat compelling
☐ Somewhat not compelling
☐ Not compelling
☐ Not compelling at all

Comments:

Peripheral cue impressions
If the concept is ***not*** the HUD orange peel: how well did you notice the peripheral cues from this concept?

- □ Very well, strong impressions
- □ Well enough, it did leave peripheral impressions
- □ Rather vague, no strong peripheral impressions
- □ Peripheral cueing was weak or hindered
- □ Different reflections from instrument panel and windows are disturbing
- □ Peripheral cueing gave the sense of climbing or descending rather than rolling
- □ Other (specify):

Comments:

Helpfulness of the audio concept (HTAWS)

In case ***only*** the HTAWS was functioning on board, please answer how helpful the concept was, otherwise go to the point "**Interaction between concepts**":

- □ very helpful
- □ helpful
- □ not certain
- □ not helpful
- □ not helpful at all

Comments:

In case you weren't sure, or it was not helpful, please specify below why not (you may tic more than one box):

- □ Too many alerts
- □ Alert sounded too early
- □ Alert sounded too late
- □ No alert was given, even though it should have
- □ Other (specify):

Comments:

Interaction between concepts
In case a visual enhancement concept was active in conjunction with the HTAWS, please answer the questions below, else go to chapter "**Flight safety**".

Express your opinion of having the HTAWS in combination with the visual enhancement concept (you may tic more than one box):

□ HTAWS is a very good addition to the visual enhancement concept
□ The HTAWS did add something, but not much
□ The HTAWS by itself was good enough, all that I needed
□ The combination of HTAWS with the visual enhancement was sometimes confusing
□ HTAWS alert did not match the impression given by the visual enhancement concept
□ No HTAWS alert was given even though it would have been appropriate
□ The repeated HTAWS alerts are annoying
□ Other (specify):

Comments:

Flight safety

How safely did you think the flight progressed (tic only one box)?

□ Very safe
□ Safe
□ Rather safe (unsure)
□ Somewhat unsafe
□ Unsafe
□ Not safe at all
□ Crash

Comments:

Why did you rate the flight safety the way you did (you may tic more than one box)?

- □ Enough altitude margins
- □ No attitude excursions beyond 30 degrees
- □ Too high a rate of descent when below 1000 ft
- □ Too small altitude margins
- □ Too large attitude excursions (beyond 30 degrees)
- □ Crash occurred
- □ Other (specify):

  \- -

  \- -

Comments:

Appendix A.2 Post Exercise Questionnaire (PEQ)

Pilot's name:

Date:

A relative comparison of the various visual enhancement concepts is made using pairwise comparisons. The comparative ratings will be done in terms of pilot preference, pilot's acceptance and ease of interpretation of the various concepts.
Also for the audio alerting concept (HTAWS) similar questions will be asked. Encircle the desired answers.

Pilot's preference of enhancement concepts

<table>
<tr><td rowspan="4">I prefer concept 1
(Malcolm Horizon)</td><td colspan="3">Equal to</td><td rowspan="4">Concept 2
(LEDs)</td></tr>
<tr><td>Somewhat</td><td rowspan="3">More than</td><td rowspan="3">Less than</td></tr>
<tr><td>Much</td></tr>
<tr><td>Very much</td></tr>
</table>

<table>
<tr><td rowspan="4">I prefer concept 3
(orange peel)</td><td colspan="3">Equal to</td><td rowspan="4">Concept 1
(Malcolm
Horizon)</td></tr>
<tr><td>Somewhat</td><td rowspan="3">More than</td><td rowspan="3">Less than</td></tr>
<tr><td>Much</td></tr>
<tr><td>Very much</td></tr>
</table>

<table>
<tr><td rowspan="4">I prefer concept 2
(LED)</td><td colspan="3">Equal to</td><td rowspan="4">Concept 3
(orange peel)</td></tr>
<tr><td>Somewhat</td><td rowspan="3">More than</td><td rowspan="3">Less than</td></tr>
<tr><td>Much</td></tr>
<tr><td>Very much</td></tr>
</table>

Comments as to why:

Would you like to have the HTAWS present with any of the visual enhancement concepts?
□ yes □ no □ HTAWS alone is good enough for me

If 'yes', then with which visual enhancement concept would you like the HTAWS to be combined with (you may tic more than one box)?

□ Malcolm Horizon
□ Peripheral + fwd + running LEDs
□ HUD orange peel with ground bar

Comments:

Pilot's acceptance of visual enhancement concepts

<table>
<tr><td rowspan="4">I accept concept 1 (Malcolm Horizon)</td><td colspan="3">Equal to</td><td rowspan="4">Concept 2 (LEDs)</td></tr>
<tr><td>Somewhat</td><td rowspan="3">More than</td><td rowspan="3">Less than</td></tr>
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<tr><td>Much</td></tr>
<tr><td>Very much</td></tr>
</table>

Comments:

Pilot's acceptance of the audio concept (HTAWS) as stand-alone system

☐ fully accepted

☐ accepted

☐ neutral

☐ rejected

☐ fully ejected

Comments:

Ease of interpretation of visual enhancement concepts

<table>
<tr><td rowspan="4">I interpret concept 1 (Malcolm Horizon)</td><td colspan="3">Equal to</td><td rowspan="4">Concept 2 (LEDs)</td></tr>
<tr><td>Somewhat</td><td rowspan="3">More easily than</td><td rowspan="3">Less easily than</td></tr>
<tr><td>Much</td></tr>
<tr><td>Very much</td></tr>
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<table>
<tr><td rowspan="4">I interpret concept 3 (orange peel)</td><td colspan="3">Equal to</td><td rowspan="4">Concept 1 (Malcolm Horizon)</td></tr>
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<tr><td>Much</td></tr>
<tr><td>Very much</td></tr>
</table>

Comments:

Compelling nature of concepts of visual enhancement concepts

<table>
<tr><td rowspan="4">I find the compelling nature of concept 1 (Malcolm Horizon)</td><td colspan="3">Equal to</td><td rowspan="4">Concept 2 (LEDs)</td></tr>
<tr><td>Somewhat</td><td rowspan="3">stronger than</td><td rowspan="3">weaker than</td></tr>
<tr><td>Much</td></tr>
<tr><td>Very much</td></tr>
</table>

<table>
<tr><td rowspan="4">I find the compelling nature of concept 3 (orange peel)</td><td colspan="3">Equal to</td><td rowspan="4">Concept 1 (Malcolm Horizon)</td></tr>
<tr><td>Somewhat</td><td rowspan="3">stronger than</td><td rowspan="3">weaker than</td></tr>
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<tr><td>Much</td></tr>
<tr><td>Very much</td></tr>
</table>

Comments:

Needed modifications or additional features

Do any or all of the enhancement concepts need additional features or changes, in your opinion?

Malcolm Horizon	HUD orange peel	LEDs	HTAWS
□ Yes □ No	□ Yes □ No	□ Yes □ No	□ Yes □ No

If answered with ‘yes’, indicate below which additional features or changes you would like to see (you may tic more than one box)

Malcolm Horizon
□ Add obstacle or terrain information
□ Make the line also “shine” inside the cockpit
□ Other (specify)

Comments:

HUD orange peel

☐ Add obstacle or terrain information

☐ Make red bar move with roll angle

☐ Remove red bar (I can do without it)

☐ Make peel less sensitive to pitch angle

☐ Make peel more sensitive with pitch angle

☐ Make symbology brighter, i.e. more clearly seen against the background

☐ Other (specify)

Comments:

LEDs

☐ Make it more sensitive in roll

☐ Make it more sensitive in pitch

☐ Make vertical speed cue also move down instead of only up

☐ Reduce brightness of LED lights

☐ Other (specify):

Comments:

HTAWS

☐ Make it give less repeated messages

☐ Improve phraseology used (e.g. “mountains” instead of “terrain”)

☐ Have it installed permanently in the aircraft

☐ Other (specify):

Comments:

Appendix B Technology Readiness Levels

The use of Technology Readiness Levels (TRL) provides a structured means of measuring and communicating the maturity of technologies within research programs. The technique complements other means of program risk assessment. Also, by assessing the risk of achieving each technology readiness level it is possible to determine, and hence manage, the risk within individual technology programs. For the HDVE project, the following TRL framework will be used. It is based upon the criteria used by the UK MoD with descriptions amended to be more generic.

Table 6 Maturity TR description

Low	1	Basic principles of technology observed & reported
	2	Technology Concept and/or Application Formulated
	3	Analytical and Laboratory Studies to validate analytical predictions
Medium	4	Component and/or basic sub- system technology valid in lab environment
	5	Component and/or basic sub-system technology valid in relevant environment
	6	System/sub-system technology model or prototype demo in relevant environment
High	7	System technology prototype demo in an operational environment
	8	System technology qualified through test & demonstration
	9	System technology 'qualified' through successful operations

Appendix B.1 Technology Readiness Level Descriptions

1. **Basic principles observed and reported.**
The lowest level of technology readiness. Scientific research begins to be evaluated for aerospace applications. Examples might include paper studies of a technology's basic properties.

2. **Technology concept and/or application formulated**.
Invention begins. Once basic principles are observed, practical applications can be postulated. The application is speculative and there is no proof or detailed analysis to support the assumptions. Examples are still limited to paper studies.

3. **Analytical and experimental critical function and/or characteristic proof of concept**.
Analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology are undertaken. Examples include components that are not yet integrated or representative.

4. **Technology component and/or basic technology sub-system validation in laboratory environment.**
Basic technology components are integrated. This is relatively "low fidelity" compared to the eventual system. Examples include integration of "ad hoc" hardware in a laboratory.

5. **Technology component and/or basic sub-system validation in relevant environment**.
Fidelity of sub-system representation increases significantly. The basic technological components are integrated with realistic supporting elements so that the technology can be tested in a simulated environment. Examples include "high fidelity" laboratory integration of components.

6. **Technology system/subsystem model or prototype demonstration in a relevant environment.**
A representative model or prototype system, which is well beyond the representation tested for TRL 5, is tested in a relevant environment. It represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high fidelity laboratory environment or in simulated operational environment.

7. **Technology system prototype demonstration in an operational environment**.
Prototype near or at planned operational system. It represents a major step up from TRL 6, requiring the demonstration of an actual system prototype in an operational environment, such as in an aircraft or vehicle. Information to allow supportability assessments is obtained. Examples include testing the prototype in a test bed aircraft.

8. **Actual technology system completed and qualified through test and demonstration**.
Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of Demonstration. Examples include test and evaluation of the system in its intended platform to determine if it meets design specifications, including those relating to supportability.

9. **Technology System “qualified” through successful operations**.
Application of the technology in its final form and under operational conditions, such as those encountered in operational test and evaluation and reliability trials.

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