Integration of a helmet-mounted display for helicopter operations in degraded visual environment: a human factors perspective

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Abstract

Helicopter operations in degraded visual environment (DVE), especially brownout/whiteout landings often result in severe incidents and accidents in the civil and military field. In fact, landing in desert environment is the most dangerous aspect of flying in combat helicopters according to the USAF. The integration of a helmet-mounted display (HMD) can help the pilot to maintain situation awareness, avoid spatial disorientation and reduce workload. Nevertheless, if not integrated properly, drawbacks (e.g. clutter, field-of-view, display latency, symbology legibility etc.) may lead to perceptual problems, attentional tunnelling and wearing discomfort. In a simulator study, DLR compared three different brownout symbology sets and three display formats (HMD monocular, HMD binocular, head-down) during a DVE approach and a whiteout landing. Flight performance, situation awareness and pilot workload were assessed. Furthermore, a detailed debriefing covered visual, perceptual and somatic aspects of helmet-mounted display use and an evaluation of the symbology sets. The paper will first discuss general human factors aspects associated with helmet-mounted displays in helicopter operations, provide an overview on symbology design considerations and finally present selected results of the conducted study.

Introduction

Helicopter operations are challenging. They may commence at short notice, have to be performed under time pressure, close to the ground and obstacles and may also require landing on unprepared landing sites. Furthermore, they need to be independent from time of day, precipitation and surface property. Especially during landing, pilots are usually trained to rely on outside visual cues in order to maintain the helicopter in a safe and stable state. When operating in adverse weather (fog, snow etc.) the impaired outside visibility makes the task particularly challenging. Visual cues that provide important information about attitude, height, descent rate or drift as well as terrain features, obstacles and hazards on the ground are missing. However, not only adverse weather may lead to a loss of outside visual references. Especially when landing in desert areas, sand is being stirred up by the rotor downwash blocking the outside visibility. This event is referred to as brownout and can also occur during landing in snow (whiteout) or over water. According to the

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NATO Rotary Wing Brownout Mitigation Report (2012), three major pilot misperceptions may arise during a brownout landing. First, pilots are unaware of lateral drifts leading to unrecognized spatial disorientation. Secondly, visually induced sensation of self motion (vection) due to the movement of the sand particles can give the pilot the erroneous sensation of turning or banking. Finally, the brownout contributes to the somatogravic illusion, giving the pilot the false impression of the helicopter pitching down when decelerating. As a consequence, impaired situational awareness may lead to rollover, hard landings and collision with surface hazards or even other helicopters. In any case, rotary wing brownout is a major problem especially in the military field. NATO (2012) reports brownout to be responsible for 75% of all helicopter incidents within NATO and the largest cause of airframe loss in the US services. Therefore new display and symbology concepts are being developed to provide the pilot with additional information when flying in DVE. Current design solutions mostly comprise 2D or more recent conformal 3D symbology sets displayed on a panel-mounted display or a HMD.

Theoretical background

In general three different types of HMD are distinguished. Monocular displays depict the symbology only to one eye, while biocular and binocular displays present the image to both eyes. (Velger, 1998) In biocular displays, exactly the same image is depicted to each eye while in binocular displays two visual images from two sensors are presented (Rash, 1999). Within the past years, several advantages of HMD have been stressed out. First, similar to head-up displays (HUD) scanning time between the instrument information and the outside scene is decreased due to superimposing the symbology in the forward field of view (McCann & Foyle, 1994). Further, visual reaccommodation is reduced because symbology is collimated (Fadden et al., 2001). Unlike in a HUD no stable head position is required to view the symbology which provides a higher freedom in movement. Finally, HMD allow for the presentation of 3D conformal, world-referenced information (Yeh et al., 1998). One major advantage of conformal symbology is that it facilitates the mental integration of information in the outside scene and the symbology presented (Wickens, 2003). This was found to provide benefits regarding guidance and navigation as well as reduction of attentional capture (McCann & Foyle, 1995). The authors further point out the importance of scene-linking for nap-of-the-earth helicopter operations and low visibility approaches. Pilots also report higher situation awareness with a HMD compared to a HUD (Arthur et al., 2009). Nevertheless, several costs are associated with HMD as well. Clutter within the forward field of view may hinder the pilot to detect targets in the outside scene (Yeh et al., 1999). Moreover, visual problems have been found including reading problems due to luminance and contrast in bright light and problems in adapting to changing light levels (Korn et al., 2009). Schmerwitz et al. (2006) report bad legibility and watery eyes as well as reduced peripheral vision due to the framing of the combiner with monocular HMDs. Perceptual and attentional problems also comprise binocular rivalry and attentional tunneling. Patterson et al. (2006) provide a great review on visual perception issues and binocular rivalry in HMD (2007). Patterson (2007) further discusses perceptual and human factors issues in 3D displays. The authors also report somatic issues such as eye strain, headache and simulator sickness with the use of HMD, leading to wearing discomfort. Simulator sickness was found to be increased particularly as exposure duration increases (Moss & Muth, 2011).

The present study focuses primarily on the evaluation of the visual, perceptual and somatic aspects associated with a HMD, a comparison of the brownout symbology sets and the effects of display type (head-down vs. helmet-mounted) on performance.

Method

Participants

Twelve male helicopter pilots participated in the study. The mean age was 43 years (SD=8), flight experience averaged 1738 flight hours on the helicopter currently operated (SD=1789) and 3925 flight hours in total (SD=3078). Within the last twelve months, they flew 191 hours (SD=145) and 26 hours in the simulator (SD=30) on average. Seven were civil and five were military pilots. Eight pilots held a VFR+IFR rating while four were solely rated in VFR. Ten pilots had already experienced a brownout in real flight before and four had trained it in the simulator. None of the experienced brownout situations have had consequences such as an incident or accident. Only one participant had prior experience with the use of a HMD, although all pilots averaged 275 hours (SD=292) experience with night vision goggles. All pilots had normal or corrected to normal eyesight. Four of them wore glasses during the flights, nobody wore contact lenses. Six pilots had right eye dominance and six pilots left eye dominance. Participants were not paid for their contribution.

Simulation Environment

The experiment was conducted in the Generic Cockpit simulator (GECO), a fixed based simulator with a field-of-view of 180 by 40 degree and a collimated vision system (figure 1). Three projection channels (each with 1280 x 1024 pixels, projected as 60 x 40 degree image) are rendered by the software ALICE which was developed by DLR. X-Plane was applied as flight simulation kernel. A center stick and a collective stick were integrated as helicopter control elements. The helicopter model simulated was a Sea King S61. The head down display was a state-of-the-art panel mounted color multifunction display (MFD). The helmet system used was the JEDEYE Helmet System prototype purchased from Elbit Systems, Israel (figure 2). It features a monochrome green binocular HMD with 1920x1200 pixels for each eye and a field of view of 80x40 degree. The helmet is further equipped with a high precision magnetic head tracker with a < 0.05 degree resolution and a < 0.25 degree accuracy.

Figure 1. Generic Cockpit Simulator (GECO)

Figure 2. JEDEYE helmet system

Symbology concepts

Three different symbology sets were evaluated. A standard PFD was used for the control condition. The symbology sets are originally not designed as a precision approach system but to assist the pilot in landing during a loss of the outside visual reference in VFR flight. Figure 3 gives a detailed description about the common concept of the symbology sets based on the BOSS display. The description also applies to the DEVILA and JEDEYE symbology since they are very similar to BOSS. The displays contain elements of a primary flight display (PFD) and navigation display (ND) and combine a forward and a top view (figure 4).

BOSS

The Brownout Symbology System (BOSS) was developed by the US Army Aviation and Missile Research Development and Engineering Center (AMRDEC). It can be used either as a head-down or a HMD. When used as a head-down display, terrain imagery can additionally be presented in the background. In this experiment however, no terrain imagery was depicted. Regularly, the BOSS display features an enroute page and a hover-approach-take-off page (HAT), yet only the HAT was used in the study. A detailed report on the BOSS symbology, its development and evaluation can be found in the NATO Brownout Report (2012).

DEVILA

The DEVILA symbology was developed by Cassidian Germany and consists of a modified BOSS symbology set to be applied for the German army CH53 helicopter. It contains less information than the BOSS display, lacking target speed, engine torque, flight path marker and the roll angle scale. Further, the radar altitude with the rising deck and the vertical speed scale are depicted on the left side of the display.

JEDEYE

The JEDEYE symbology was developed in 2011 by Elbit Systems, Israel and the DLR Institute of Flight Guidance with consultancy from the German Armed Forces. It is predominantly based on the BOSS symbology but provides less clutter within the field of view. Also, radar altitude and vertical speed are presented on the left side like in the DEVILA symbology due to stimulus-response compatibility reasons. Further specifications on the JEDEYE symbology are found in Döhler et al. (2012).

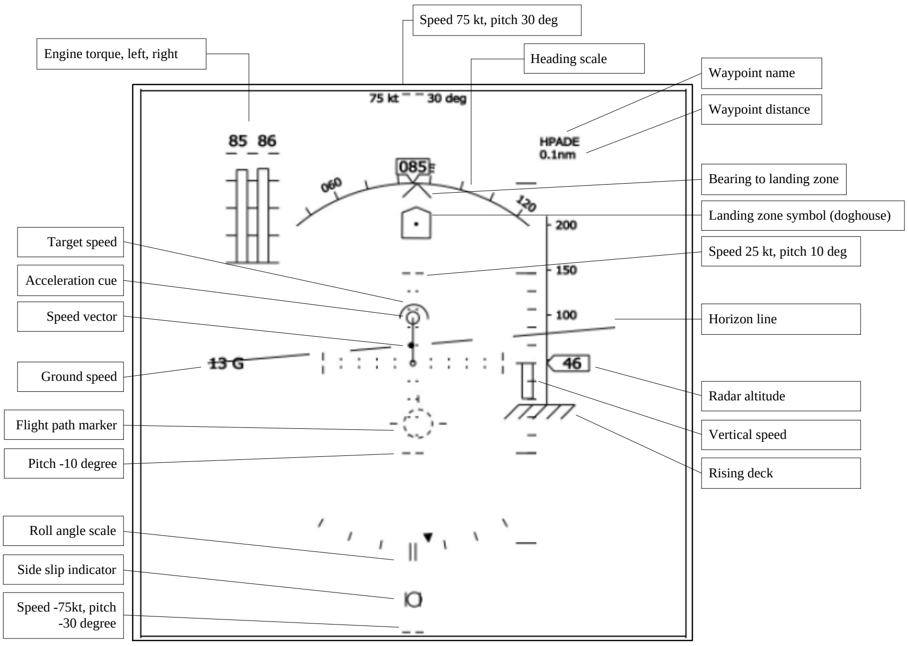

Figure 3. BOSS symbology

Procedure

Pilots first completed a biographical questionnaire and were briefed about the HMD, the simulator and the symbology sets. An eye-dominance test was then conducted to determine in front of which eye the monocular symbology had to be presented. Subsequently they started the training session in the simulator. A fifteen minutes free training was conducted to familiarise with the simulator and its handling qualities. Afterwards the approach scenarios' visual cues, heading, speed and altitude changes were memorized and rehearsed. Finally, pilots trained the symbology sets and the helmet use to become accustomed to the symbology in the forward field-of-view. The total briefing and training time was about three hours. Breaks were scheduled according to the pilots' preference. Moreover pilots were briefed about the questionnaires used in the experiment. Afterwards the test flights started. The pilot was seated on the right side and the experimenter was seated on the left. The experimenter supervised the test flight and handed the questionnaires to the pilot after each scenario but did not actively participate in the flight as a copilot. At the end pilots filled out a debriefing questionnaire which assessed ratings on overall helmet comfort, visual, perceptual and somatic aspects as well as an evaluation of the symbology sets.

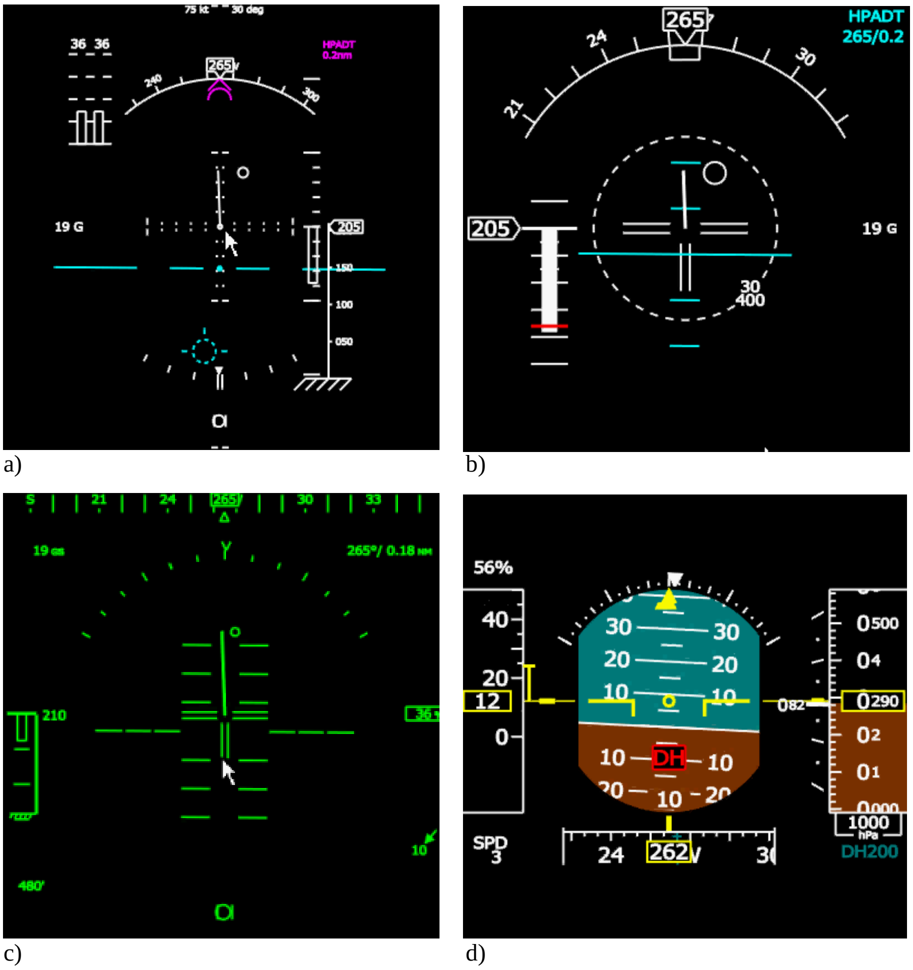

Figure 4. Symbology sets used in the experiment: a) BOSS, b) DEVILA, c) JEDEYE, d) PFD as control condition

Experimental Design and Task

Experimental variations consisted of type of symbology, type of presentation, type of approach route and wind condition. Every pilot flew a total of 24 scenarios, respectively a block of six scenarios with each symbology set. Symbology type, approach route and wind condition were counterbalanced. The PFD and the BOSS conditions were flown head-down. On the contrary, pilots flew the DEVILA symbology monocularly and the JEDEYE symbology binocularly on the HMD. The PFD was covered with a board when flying with the symbology to ensure that pilots actually oriented themselves on the symbol set and not on the PFD. The scenarios consisted of two different approach routes that were flown alternately. Approach route MIKE started in the west of Brunswick (EDVE) airport and approach route NOVEMBER started in the north. Pilots were briefed to navigate based on landmarks and instructed to change heading, speed and altitude at defined positions (figure 5). All scenarios started at an altitude of 800ft and with an airspeed of 90 knots. The helicopter was the only aircraft in the control zone. There was no VHF communication between the pilot and the ground controller. The final descent was identical for both approach routes. It started 0.3 nautical miles away from the landing point at about 300 ft AGL. The landing point was situated at the extension of runway 08 at Brunswick Airport and was marked with an arrow on the ground. A marshaller was positioned 20 meters next to the landing zone. He pointed his arms downward clearing the pilot to land. The marshaller was only fully visible if the pilot landed in close proximity to the defined landing zone. All scenarios were flown in special VFR conditions with nebulous weather. Flight view was about 1.8 nautical miles. A whiteout was simulated by heavy ground fog below an altitude of 35 ft above ground. However pilots did not lose the full outside visual reference because the runway lights provided some orientation. Each approach was flown in three different wind conditions. Wind direction varied between straight, left and right. Wind changed from 15 kt above 500 ft AGL down to 6 kt on the ground. All scenarios were flown with the helmet visor down independently from symbology condition to provide for constant brightness and contrast of the outside view. For the head-down conditions there was no symbology presented on the visor. Pilots completed the NASA Task Load Index (Hart & Staveland, 1988) and the Situation Awareness Rating Technique (Taylor, 1990) after each scenario.

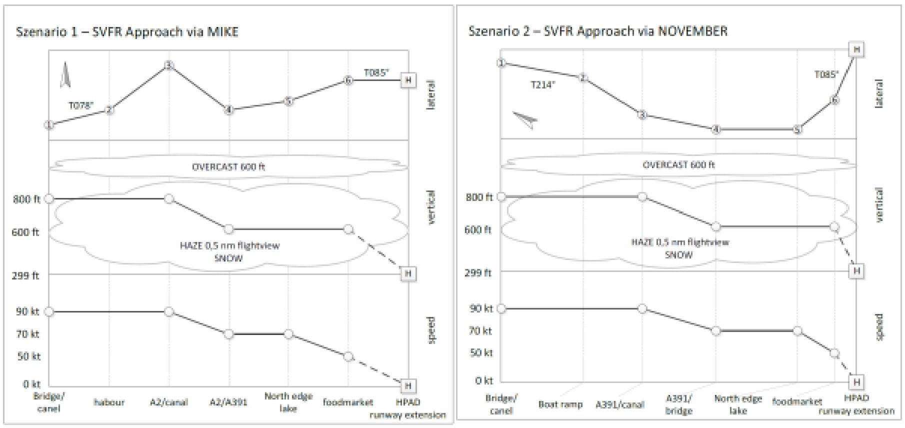

Figure 5. Approach routes specifications

Unexpected Event

An unexpected, unbriefed event occured in one scenario for each pilot. The marshaller held his arms crossed above the head signalising the pilot to abort the landing. The event was designed to evaluate which display concept respectively which type of information presentation allows for a better detection of an off-nominal event. Verbal acknowledgment as well as abortion of the landing were accepted as a successful detection. The event was counterbalanced over the display concepts and therefore occured for each pilot in a different scenario.

Results

Flight test results

Flight performance
Flight test analyses consisted of comparisons between the four display types regarding sinkrate and ground speed for the final approach segment from top of decent until 50 ft AGL (approximately 90 meters before the landing point) as well as orientation heading and lateral deviation from the defined landing point at touchdown. Repeated Measures Analyses of Variance (ANOVAs) were conducted with a p value of .05 for statistical significance and .10 for a tendency approaching significance. Results did neither reveal any significant differences nor any tendencies.

Situation awareness and workload
Repeated measures ANOVAs were performed for NASA TLX and SART data. No significant differences between the four display formats were found.

Unexpected event
Surprisingly, only one pilot detected and commented the unexpected event. Three pilots landed too far away from the landing point so the marshaller was not visible. Eight pilots did not notice the signal to abort the landing even though the marshaller was in sight. Neither did they comment the event nor abort the landing. Pilots afterwards stated that they did not pay attention to it, did not consider it as part of the experiment and had no capacity left to search the outside scene.

Debriefing questionnaire results

Helmet mounted display ratings
First of all, pilots reported good overall wearing comfort (M=4.17; SD=0.94) and overall visual comfort (M=4.1, SD=0.9) on a scale from "1 = very poor" to "5 = very good". Visual and perceptual aspects were rated separately for the monocular and the binocular condition. T-Tests were conducted to assess differences between the ratings ($p < .05$ for statistical significance, $p < .10$ for a tendency approaching significance). In conformance with the good overall visual comfort, all visual aspects were also rated to be rather good for both display types with a small favour for the binocular display (figure 6). Symbology readibility was rated better with the binocular display (M=4.5) than with the monocular (M=3.9) approaching statistical significance $t(10)=-2.2$, $p=.05$. Furthermore, there was a tendency towards a small favour for the binocular display (M=4.4) regarding symbology contrast compared to the monocular display (M=3.9), $t(10)= -2.2$, $p=.05$.

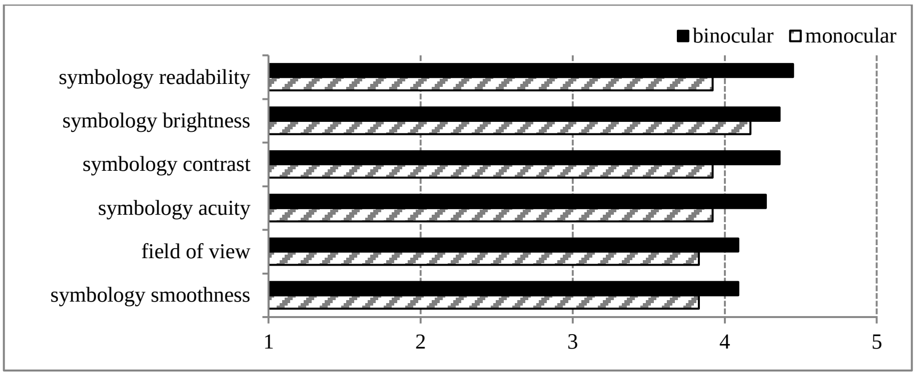

Figure 6. Visual aspects mean ratings (1: very poor, 2: poor, 3: average, 4: good, 5: very good)

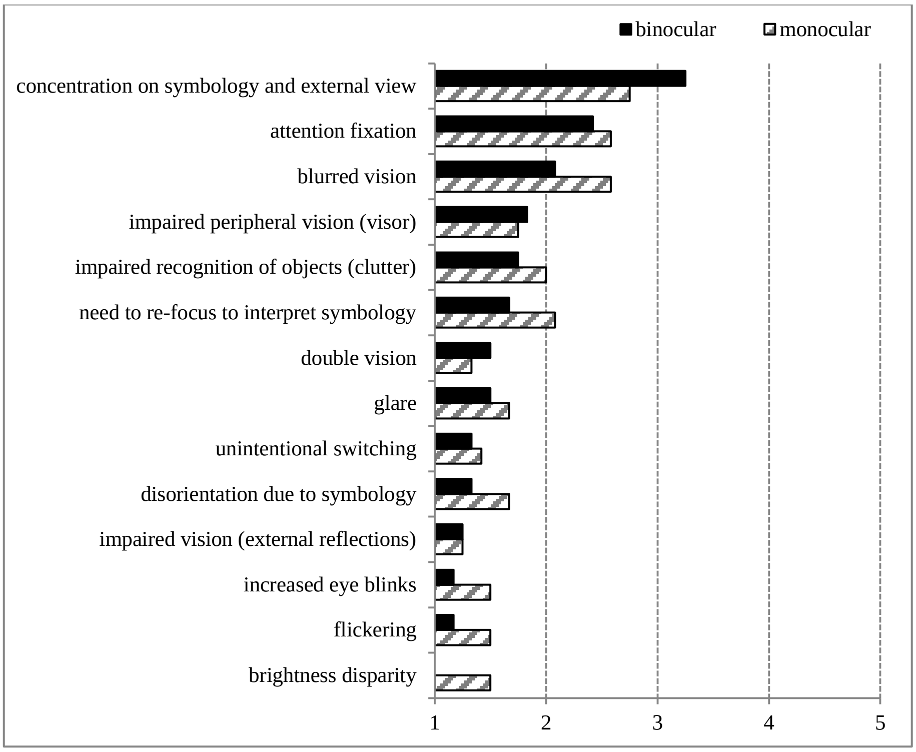

Figure 7. Perceptual aspects mean ratings (1: never, 2: rarely, 3: sometimes, 4: often, 5: always)

Pilots generally reported very few perceptual problems (figure 7). Significantly increased eye blinks and flicker were reported with the monocular display (M=1.2) compared to the binocular (M=1.5), t(11)=2.4, p=.04. Besides it was by trend easier to concentrate on the symbology and the outside scene simultaneously with the binocular (M=3.3) than with the monocular display (M=2.8), t(11)=-1.9, p=.08. Therefore pilots also needed to refocus more with the monocular (M=2.1) than with the binocular one (M=1.7), t(11)=2.2, p=.05. Four pilots reported to have rarely to sometimes trouble with brightness disparity between the eyes when using a monocular display. Nobody had this problem in the binocular condition.

Somatic aspects were also rated to be very low. Seven pilots reported weak overall fatigue rather attributed it to the test scenarios. Eye strain was the biggest issue being reported strongly by three pilots and weak to very weak by five pilots. All other somatic issues such as neck pain, headache, nausea, vertigo, watery or dry eyes were rated from "weak" to "not at all". At last eight pilots stated that purposely alternating between the symbology and external view is easy, while four stated to have some difficulties. Moreover all pilots prefered the HMD over the head-down condition independently from the symbology set. Ten prefered the binocular, two the monocular condition. There were several additional comments stated in favor for the helmet-mounted and in particular for the binocular display. Pilots commented that they are better kept in the loop by the presentation of the symbology within the forward field of view. Scanning time between the instrument information and the outside scene as well as head movements are severely reduced. This is particularly important since pilots report that eyes-out time is an absolute must during a brownout landing. Pilots also reported increased situation awareness. The binocular display was additionally favoured because it compensates for occasional blurry vision in one eye and provides better overall visual comfort, e.g. by evenly distributing eye strain on both eyes. One pilot refered to binocular rivalry with the monocular display.

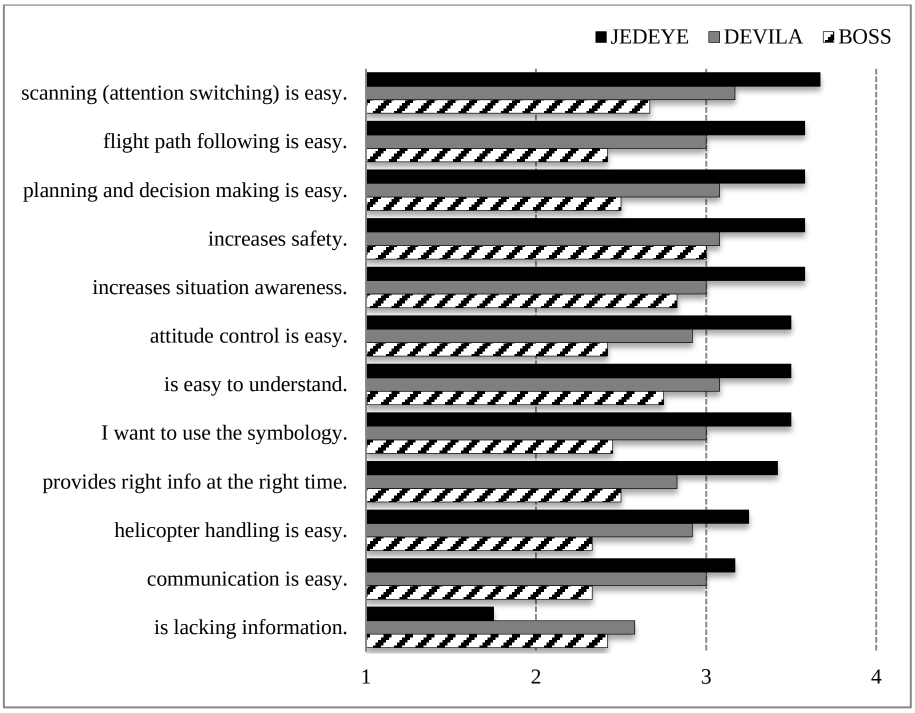

Figure 8. Symbology sets mean rating (1: strongly disagree, 2: disagree, 3: agree, 4: strongly agree)

Symbology ratings

Repeated measures ANOVAs ($p<.05$) revealed significant differences between the display ratings of the BOSS and the JEDEYE symbology (figure 8). JEDEYE was rated significantly better than the BOSS symbology. Apart from that pilots stated that the DEVILA symbology ($M=2.6$) is lacking significantly more information than the JEDEYE symbology ($M=1.8$), $F(2,22)=5.5$, $p=.01$. Further ten out of twelve pilots favoured the JEDEYE symbology, one prefered DEVILA due to little overall clutter and one BOSS. Primarily pilots comment that JEDEYE caused the lowest clutter within the forward field of view and information was presented well arranged and intuitively.

Summary and conclusion

Results did not reveal any differences in performance. Nonetheless the debriefing questionnaire showed an overall benefit for the HMD, especially for the binocular condition. Further the JEDEYE symbology was rated best. Generally it has to be stated that the simulator handling was quite challenging. Pilots reported the need to make significantly more control inputs than usually when flying and that the handling qualities were rather poor especially for the landing task. It is supposed that this is the main reason why results did not reveal significant differences. Also the restricted downward viewing angle from the (originally) fixed-wing simulator did not provide the familiar helicopter outside view. Further training time was rather short to adjust to the symbol sets. Although pilots reported good situational awareness and medium workload, the results of the unexpected event rather indicate attentional tunneling and high workload by failing to divide attention between the display and the far domain when events are not briefed. Nevertheless an overall advantage of the HMD was stressed in the pilot ratings and comments. Providing pilots with higher situation awareness when operating in DVE is still one of the most important issues regarding helicopter flight safety. Therefore, further research will particularly focus on head-tracked HMD with 3D conformal symbology as well as information on terrain and obstacle hazards.

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