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ORIGINAL ARTICLE

The virtual landing pad: facilitating rotary-wing landing operations in degraded visual environments

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Abstract
The safety of rotary-wing operations is significantly affected by the local weather conditions, especially during key phases of flight including hover and landing. Despite the operational flexibility of rotary-wing craft, such craft accounts for a significantly greater proportion of accidents than their fixed-wing counterparts. A key period of risk when operating rotary-wing aircraft is during operations that occur in degraded visual environments, for example as a result of thick fog. During such conditions, pilots' workload significantly increases and their situation awareness can be greatly impeded. The current study examines the extent to which providing information to pilots via the use of a head-up display (HUD) influenced perceived workload and situation awareness, when operating in both clear and degraded visual environments. Results suggest that whilst the HUD did not benefit pilots during clear conditions, workload was reduced when operating in degraded visual conditions. Overall results demonstrate that access to the HUD reduces the difficulties associated with flying in degraded visual environments.

Keywords Rotary-wing · Head-up display · Situation awareness · Workload

1 Introduction

A leading cause of delays at major commercial airports is low visibility during the critical phases of flight (Allan et al. 2001; Sridhar and Swei 2006). Limited visibility is also the largest contributing factor in fatal airline accidents worldwide (Federal Aviation Administration 2001). In addition to increasing flight safety, the potential economic benefits of reducing flight delays and cancellations drive the development of new technologies to increase operational capacity in degraded visual environments for civil aviation (Prinzel Iii et al. 2004; Hemm 2000; Cahill et al. 2016). The operational benefits of rotary-wing aircrafts include the capacity to fly at low altitude, take-off and land vertically, and hover with zero ground speed (Baker et al. 2011; Swail and Jennings 1999; Grissom et al. 2006; Alppay and Bayazit 2015). The ability to fly to unimproved landing sites, without aviation-related ground infrastructure, extends the potential use of rotary-wing aircraft for public transportation (BHA 2014) and, however, also leads to a greater exposure to potential risks, especially when operating in degraded visual conditions. In 2013, an accident in the UK saw the death of an experienced rotary-wing pilot and a civilian after a helicopter collided with a crane jib, whilst flying through dense fog, in central London (AAIB 2013). Erroneous pilot decision making including continued visual flight into instrument conditions and neglecting to check weather conditions was a contributing factor in 40% of rotary-wing accidents supporting gas operations in the Gulf of Mexico between 1983 and 2009 (Baker et al. 2011).

Whilst the demand for civilian helicopters with the capacity to operate in degraded visual conditions is substantial, the development of cockpit technologies to facilitate such a pursuit is in its infancy. The lack of suitable technology is apparent when compared to that available within both civilian fixed-wing aircraft or within the military domain (Doehler et al. 2009; Theunissen et al. 2005). Swail and Jennings (1999) completed a Human Factors analysis of rotary-wing search and rescue operations and highlighted that a number of mission critical elements are impossible

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to complete without advanced technology to facilitate the task. It is likely that continuing with such operations, despite the inherent safety risks, offers partial explanation for the higher accident rates associated with rotary-wing aircrafts compared to fixed-wing counterparts (Doehler et al. 2009); alongside the greater mechanical complexity and pilot skill requirements associated with rotary-wing aircrafts. The current study developed and tested a potential future cockpit technology, a new head-up display (HUD) to facilitate the operation of civilian rotary-wing aircrafts in degraded visual environments.

1.1 Situation awareness

Situation awareness can be defined as *'the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future'* (Endsley 1988, p97). According to this definition, information or knowledge concerning situation awareness is held in the working memory of an individual, supporting their comprehension and knowledge of a situation (Bell and Lyon 2000; Endsley 2000). One criticism that can be levelled at this definition, however, is that it focuses on situation awareness at the level of the individual human agent. Situation awareness may be distributed across multiple agents, both human and nonhuman, within a system (Stanton et al. 2014), as can be seen within a variety of social-technical systems, for example submarine operations (Stanton 2014) and fixed-wing aircraft operations (Stanton et al. 2016a, b). Additionally, situation awareness should not be viewed as a linear information processing construct, but rather a cyclical, parallel and dynamic activity that continuously changes across time (Harris 2011). From a systems perspective, during flight, situation awareness is distributed across the cockpit. Not all information has to be held in the working memory of the pilot, rather the optimal interaction of the socio-technical system, comprised of both the pilot and on-board technologies, maintains adequate pilot situation awareness (Stanton et al. 2010; Harris 2011).

During flight, a pilot's primary source of information is visual guidance from the outside world, especially during low-altitude operations. Visual cues therefore perform a central role informing a pilot's situation awareness (Doehler et al. 2009) and play a central role in the safety of flight operations. The primary performance factors impacting upon rotary-wing aircraft accidents near off shore drilling platforms have been identified as awareness of obstacles at the destination; sufficiency of visual cues for approach; and stability of visual cues and sufficiency of visual aids for landing as primary performance factors (Nascimento et al. 2013). Identifying what cues and information pilots require for flight during operations in degraded visual environments may be aided by understanding the information pilots utilise in optimal flying conditions. During basic rotary-wing manoeuvres, pilots rely on visual awareness of at least three external reference points in order to monitor altitude and position, as well as confirmatory information provided by the cockpit instrument panel (see squirrel HT1/2 flying guide instructions). During optimal flying conditions, pilots fly in an anticipatory fashion; flight is proactive, as pilot's routinely sample flight parameter information (Endsley et al. 1998). The cockpit instrument scanning behaviour of pilots supports the notion of confirmatory information 'checking', with more time being dedicated to the sampling of information if an unexpected discrepancy is observed (Wickens 2002; Bellenkes et al. 1997; Wickens 2001; Kasarskis et al. 2001). Alongside instrumentation checks, information from the external environment including physical geometry of terrain and objects, texture density and the rate of visual flow inform pilot situation awareness (Foyle et al. 1992).

1.2 Cognitive workload

A pilot's reliance on visual cues from the external environment becomes problematic during flight in degraded visual environments when such cues are obscured. Pilots can no longer fly in an anticipatory fashion; instead a shift is required to reactionary pursuit control where cockpit instrumentation is used to generate mental models and drive appropriate schema selection rather than to confirm such processes (Doehler et al. 2009; Snow and French 2002; Harris 2011; Klein 1997; Wickens 2002). Despite an improvement on older cockpit technologies (Harris 2011), current cockpit technologies still presents information in a coded fashion that requires extensive computation for understanding. The use of cockpit information therefore induces greater workload and increased processing time in comparison to the use of environmental cues (Prinzel Iii et al. 2004). Working memory, the cognitive system individuals' use to process task relevant information, has limited capacity making it susceptible to overload (Baddeley 2000), potentially making some required computation impossible. Cognitive demand can be defined as the mental effort an operator must expend on a task, relative to their available resources, or, the cost of information processing required when performing a given task (Harris 2011; Farmer and Brownson 2003). When operating in degraded visual conditions, the extra processing required of information presented in the cockpit instrumentation greatly increases cognitive demand. In such situations, individuals typically seek ways in which to reduce cognitive processing load (Blascovich et al. 1999). It is common for individuals to use cognitive shortcuts (heuristics) and previous experience to streamline the decision making process. Whilst the use of such techniques can reduce cognitive load and facilitate rapid decision making, they are also prone to

errors bias, reduced overall productivity and reduced performance (Harris 2011; Klein 1997).

1.3 Heads-up display (HUD) and conformal semiology

Improving pilot situation awareness and optimising workload are the primary aims of future cockpit technologies, particularly those aimed at facilitating flight in degraded visual environments (Harris 2011; Melzer 2012). The presentation of information in a HUD does not require the pilot to divert visual attention and cognitive resources into the cockpit, such as required with traditional head-down displays (HDD). This in turn reduces the requirement to direct gaze and attention away from external events and primary flight references, potentially reducing workload and increasing situation awareness (Snow and Reising 1999; Ververs and Wickens 1998; Snow and French 2002). A HUD is a glass mounted panel in the pilots near visual field that displays flight information, typically 2D traditional flight references (e.g. airspeed, altitude and power) and a 3D (conformal) graphical representation of the outside environment (Swail and Jennings 1999; Thomas and Wickens 2004; Prinzel Iii et al. 2004). A further potential application of the HUD is the presentation of an integrated graphic flight path representation, often termed 'a highway in the sky' (HITS, Thomas & Wickens 2004). The primary objective of the HITS is to facilitate the tasks of flying and navigating (Alexander et al. 2003). HITSs have been shown to facilitate increased maintenance of lateral and vertical flight path awareness (Williams et al. 2001) and the inclusion of synthetic terrain has been shown to significantly increase the situation awareness improvement potential of HITSs (Snow and Reising 1999).

A HUD allows pilot to fly 'eyes out' rather than switching attention to the cockpit HDDs. Conformal symbology provides a detailed, realistic representation of the terrain in front of the aircraft and potential obstacles present within the local environment at low altitude (Thomas and Wickens 2004). The presentation of synthetic environmental information in a HUD, compared to HDDs, has been shown to improve pilot performance (Prinzel Iii et al. 2004). Conformal symbology leads to faster detection response to changes in symbology and improved flight path tracking accuracy (Fadden et al. 1998; Snow and French 2002). Furthermore, data from real flight studies have indicated that conformal symbology provides improved path control and situation awareness in terrain-challenged operating environments (Prinzel et al. 2002). Whilst currently, HUDs are typically cockpit glass panels, future cockpit technologies are looking to extend the potential of such displays to be embedded more holistically within the cockpit, offering greater freedom of view opposed to the more narrow forward facing view currently available. Although current head-mounted displays are available, Frey (2011) argued that new technology will only succeed whether it increases perceived freedom and control. The use of full cockpits HUDS, with greater perceived freedom, as pursued in this study, is therefore preferable.

Whilst the benefits of HUDs are well documented, there is debate concerning their usefulness and concerns regarding their potential to negatively affect pilot behaviour. The HUD is useful for anticipated events; however, the detection of unexpected events may be degraded by attentional tunnelling (Fadden et al. 1998). This occurs when attention is allocated to a particular channel of information (e.g. HITS), for longer that is optimal, resulting in other task relevant information or additional tasks being neglected, for example potential risk objects within the external environment (Wickens and Alexander 2009; Snow and French 2002). Due to the potential negative outcomes associated with HUD use, the development and design of this technology is critical. Functional benefits including easier access to information and facilitated flight performance must be maximised whilst the potential for negative behaviours, such as attentional tunnelling must be minimised. To maximise the benefits of HUDs, designers must preserve the most useful and unambiguous visual cues pilots naturally use so that information is processed intuitively (Foyle et al. 1992; Harris 2011; Prinzel Iii et al. 2004; Ververs and Wickens 1998; Klein 1997). An overly cluttered HUD can be detrimental to pilot task performance and situation awareness, particularly when task irrelevant information is presented in demanding situations (Yeh et al. 2003). The presentation of intuitive and useful flight information in a HUD may also be useful in clear visual conditions, not just in terms of the reduced visual scan required but also to facilitate integration of different information forms (Ververs and Wickens 1998).

1.4 Current study and experimental hypotheses

The current study aims to develop and assess the usefulness of a HUD with 2D flight semiology and 3D conformal semiology. The use of flight simulators to explore the Human Factors issues which could emerge through the use of novel flight instrumentation and technology is an established research trend (Oberhauser and Dreyer 2017). The current work is the refinement of a HUD previously tested which was shown to improve pilot situation awareness and reduce workload (Stanton et al. 2016a, b). In this study, a number of problems were highlighted with the HUD; Firstly, pilot awareness of power was impaired across all experimental conditions; suggesting the manner in which power was represented was inadequate. Secondly, the HUD did not affect pilot awareness of rate of descent and drift. The current study tested the effectiveness of an iteration of the HUD concept, which aimed to retain the functional benefits

of the previous design, whilst simultaneously targeting the issues encountered in earlier designs. A further methodological issue when testing the initial HUD concept was a small sample size. The current study uses a larger sample size to conduct an evaluation with greater statistical power.

Based on the results obtained using the initial HUD design and previous research within the field, it is hypothesised that:

1. Pilot workload will be reduced and situation awareness increased in degraded visual conditions when pilots have access to the HUD compared to degraded visual conditions without HUD.
2. No difference in workload or situation awareness will be observed between flight in degraded visual conditions with HUD and clear visual conditions without HUD.
3. The HUD shall have no detrimental impact on performance during clear visual conditions (i.e. no difference in workload or situation awareness with and without HUD during clear flight).

2 Method

2.1 Participants

Thirteen male subjects aged 21–66 years (M = 47.69, SD = 13.38) took part in the study. Participants were recruited using advertisement posters disseminated at local airfields alongside recommendations from acquaintances of pilots who had previously participated within the research study. All participants were qualified rotary-wing pilots with varying amounts of rotary-wing flight hours, 45–8400 (M = 3415, SD = 2987), flown. All participants had piloted, a real aircraft or a high fidelity simulator, within a year of the study. Ethical permission for this study was granted by the Research Ethics Committee at the University of Southampton and all participants provided informed written consent.

2.2 Design

The study employed a 2 × 2 within-subjects design. The independent variables were weather condition (clear sky or degraded visual environment) and symbology used (with or without HUD). The order of presentation of the conditions was counterbalanced between the participants. In addition to the basic study design, all participants completed a base flight prior to the experimental conditions on the same flight profile as the experimental conditions, in clear weather without the HUD. The base flight was repeated at the end of the experiment to examine whether familiarisation with the flight model across the experimental conditions had impacted upon results.

2.3 Equipment and materials

2.3.1 Flight simulator

A fixed-based flight deck simulation facility at the University of Southampton was used (rotary-wing configuration). The simulator was comprised of a two-seater cockpit with five multi-function display units. The external view, as would be seen from the cabin, was presented across three desktop monitors. This setup provided a 140° out of the window field-of-view. Participants were seated in the right-hand seat which was configured with rotary-wing controls. The simulated environment ran using Prepar3D (previously Microsoft flight simulator software). Prepar3D software is highly customisable and allowed the required weather conditions to be simulated. The flight scenario was located over a helipad at the Norfolk naval base, Virginia, USA, using the Eurocopter flight model. This model was chosen to be a more stable helicopter than the Bell 206 used within previous work (Stanton et al. 2016a, b). In the clear sky conditions, the clear weather setting was selected, allowing pilots a considerable view. In the degraded visibility conditions, the fog setting reduced visibility to approximately 0.5 km. The flight controls were the rotary-wing Pro-Flight Trainer evolution control system, consisting of the anti-torque pedals, collective and cyclic. The flight controls interfaced with the flight simulator via a USB connection.

2.3.2 Head-down display

The head-down display (HDD) was displayed to the pilots on the laptop computer positioned in front of the three monitors. The HDD was available to the pilots throughout all four conditions. The HDD was part of the Prepar3D software and consisted of analogue flight instruments, including: attitude indicator, airspeed indicator, a compass, heading indicator, altimeter, vertical speed indicator and Torque indicator.

2.3.3 Head-up display

The development of the HUD forms part of a larger research project in which the concept was designed with the aid of Cognitive Work Analysis (see Stanton and Plant 2010, 2011; Stanton et al. 2016a, b). The primary objective of the HUD was that it would be capable of assisting the pilot with performing approach and landing in degraded visual environments. A full colour system and extended field-of-view (e.g. future windshield displays) was assumed. The HUD concept was created using GL Studio. This is a software tool specifically developed for interface display design and provides the ability for its display instruments to be controlled from external applications (e.g. Prepar3D). A two-way data interface was developed to allow flight data to be

transferred from Prepar3D and synchronised symbology to be transferred from GL studio. During the flight conditions with the HUD, the concept was overlaid onto the simulated environment using a ghost window application. The HUD contained the following 2D flight instruments: conformal compass, heading readout, airspeed indicator, gull wing horizon line, attitude indicator, vertical speed indicator, air speed indicator, wind direction and strength indicator, ground speed and distance to go. The current HUD did not include a HITS, it is hoped future versions shall include such symbology; however, in the interest of rigour, it was decided initial testing should focus on the presentation of conformal symbology at the landing site.

To assist with the landing task the HUD included (see Fig. 1):

1. 'Trampoline' rings provide visual cues for the pilot. The magenta ring represents the aircrafts orientation (i.e. moves in reference to the aircraft). The blue ring is fixed as a representation of the ground. The process of aligning the magenta ring with the blue rings was designed to assist the pilot in the touch down phase of flight, particularly when on sloped surfaces.
2. The 'bulls eye' landing zone was designed with unprepared landing sites in mind. The landing site provides the pilot with more ground perspective, and the circular design allows for different angles of approach to be made when accounting for wind direction. The central point provides a target that is easily locatable target for which to align the flight path vector.
3. The 3D augmented reality 'trees' around the outside of the helipad provide visual references for the pilot, providing a sense of speed, direction and altitude. The smaller trees towards the centre of the circle are 75 ft high and the larger ones behind are 150 ft high, providing the pilot with additional visual cuing. When the shorter trees directly align with the larger trees (i.e. only

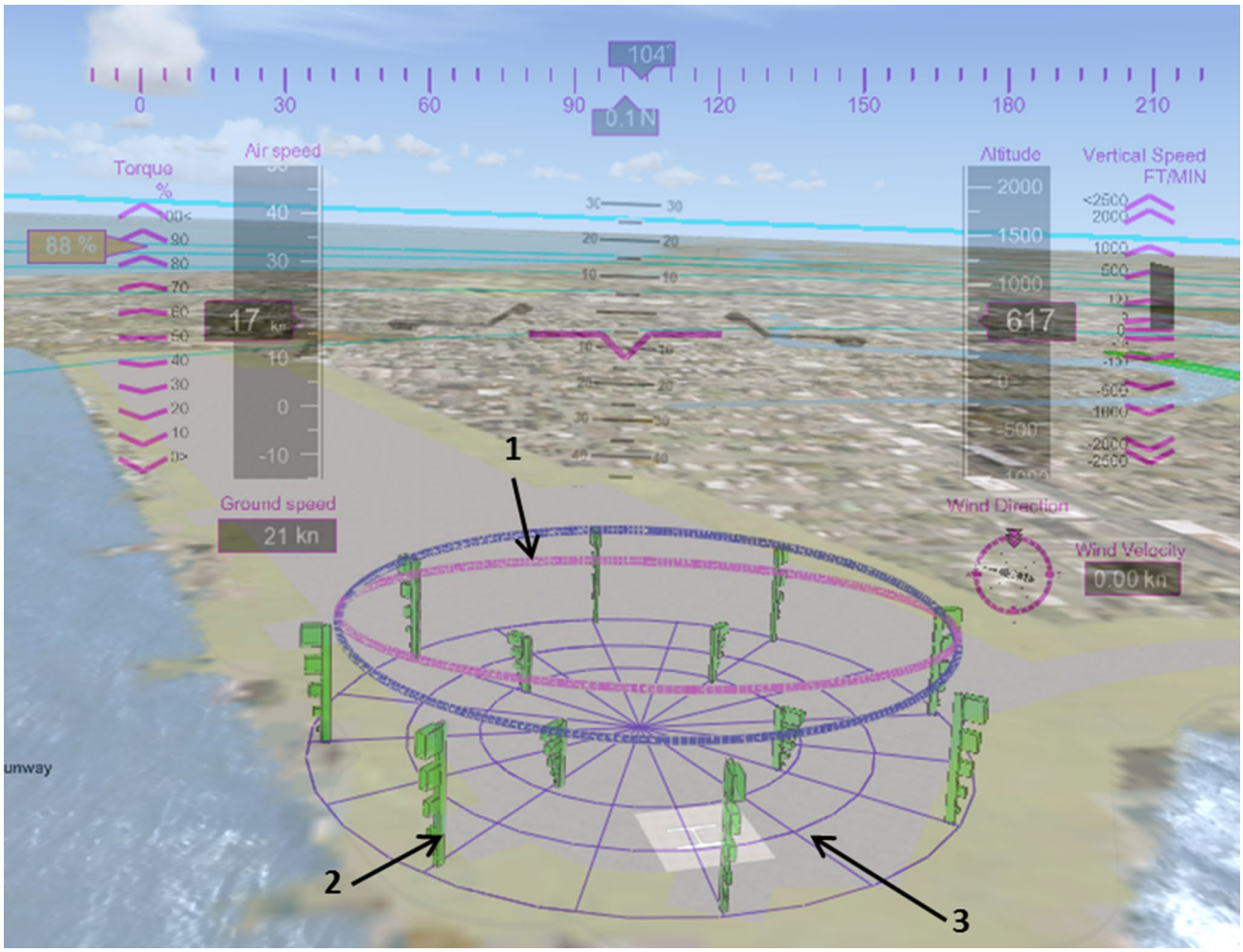

Fig. 1 Landing symbology in the HUD, clear sky condition (numbers relate to description in text above)

one tree is visible), the pilot can be sure he is directly over the centre of the landing site.

4. The flight path vector acts as a touch down indicator, this becomes visible to the pilot when losing altitude, and it represents the point on the ground they will hit if the current velocity is maintained (number 4, Fig. 2).

2.3.4 Participant questionnaires

Three questionnaires were administered to participants in order to collect subjective ratings of situation awareness and workload. The questionnaires were administered after each experimental condition had been flown. The post-landing assessment (PLA) was a bespoke questionnaire that was developed by subject matter experts on rotary-wing operations. The questionnaire asks participants to rate their awareness of various flight parameters (e.g. desired heading, desired rate of descent, power status, drift) from 1 (low) to 7 (high). The PLA also asks for a rating of how likely the pilot was to performing a go-around manoeuvre from 1 (not likely) to 7 (very likely). At the end of each flight, a debrief session was held so that the researchers could probe the pilots about reasons for their ratings on the PLA. The Bedford Workload Rating scale (Roscoe and Ellis 1990) is a unidimensional mental workload assessment technique developed to assess pilots' perceived workload. The technique involves a hierarchal decision tree to assess workload via an assessment of spare capacity whilst performing a task. Participants follow the decision tree to derive a workload rating for the task under analysis (Stanton et al. 2014). A scale of 1 (low workload–workload insignificant) to 10 (high workload–task abandoned) is used. The NASA-Task Load Index (NASA-TLX: NASA 1986; Hart and Staveland 1988) is one of the most commonly used subjective techniques to assess workload (Stanton et al. 2014). The questionnaire consists of six continuous sub-scales along which participants are asked to rate different aspects of workload: mental demand, physical demand, temporal demand, performance, effort and frustration. The sub-scales range from 0 to 100, and the ratings for each of the six sub-scales were analysed separately as well as being combined to produce an overall workload score.

2.4 Procedure

Participants were briefed about the study and asked to complete a consent form and a demographic questionnaire. Participants were then given an initial familiarisation session with the simulator which allowed them to get used to the flight model and flight controls. The participants were then familiarised with the HUD in a talk through provided by the software developer to explain each instrument and the way the conformal symbology worked. Participants were then given time to practice flying with the HUD. The familiarisation session lasted approximately 25 min. Each participant flew a baseline flight at the start of the study which was on the same flight profile as the experimental conditions and was flown in clear weather without the HUD. After baseline flight, the questionnaires were completed. The participants then flew each of the four experimental conditions (clear,

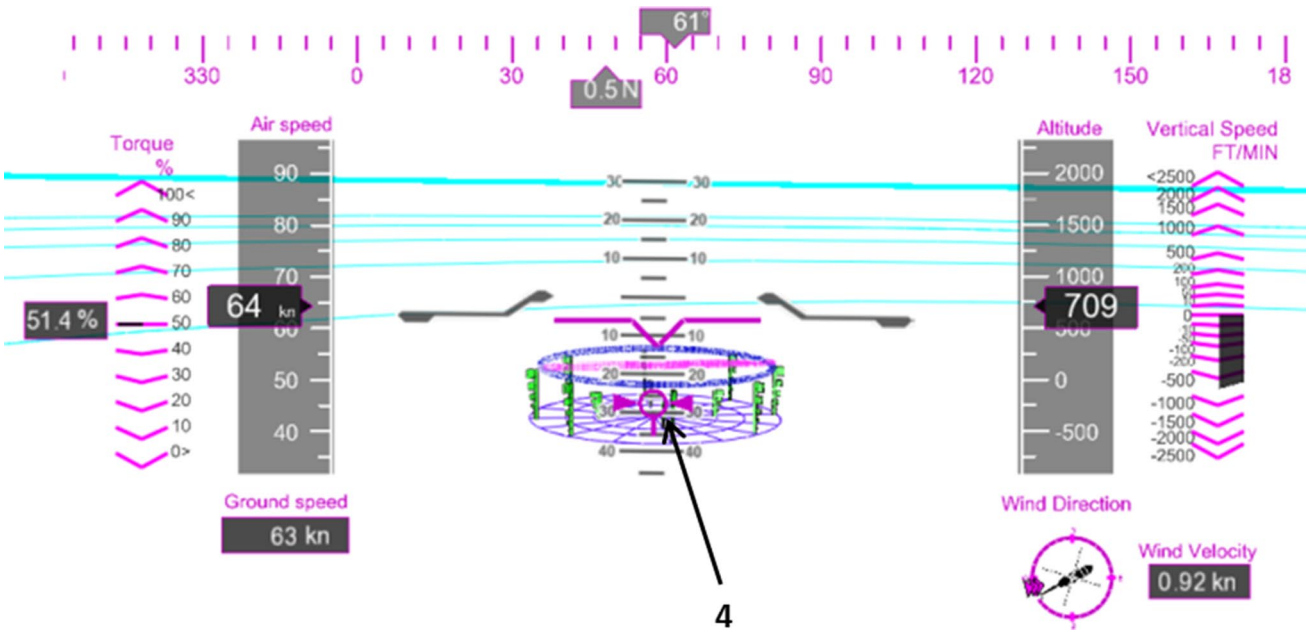

Fig. 2 Landing symbology showing the flight path vector

clear + HUD, fog or fog + HUD). For each condition participants started 5 nm out to sea and were instructed to land on the target helipad, which was visible in the clear sky conditions, and a heading was provided in the fog conditions. Participants were instructed to fly to the helipad and land the aircraft. In the fog only condition, a 15 min time limit was set and if the pilot had not found the airfield within this time, the trial was stopped. After each condition was flown, the three questionnaires were administered and a debrief session probed pilots about the reasons for their ratings. Each flight condition, including completing the required questionnaires, lasted approximately 15 min. When completing the questionnaires, the participants were instructed to detach from any feelings associated with the simulated environment (e.g. fidelity of the flight controls and flight model) and base their ratings purely on the HUD symbology and scenario under evaluation. After the four experimental conditions were flown, the pilots flew another baseline flight and completed the questionnaires. At the end of the study, a longer debrief session was held to allow pilots to comment on the symbology in the HUD. All debrief sessions were audio recorded and later transcribed.

3 Results

3.1 Data analysis

Family wise error rates were considered and collinearity examined when choosing factors to include in each statistical model. It was decided to examine all sub-factors of awareness and NASA-TLX in separate models, Bedford workload measurements and confidence scores were also examined separately.

The parametric tests reported within this paper are robust to violations of normality (Donaldson 1966; Keselman et al. 2002). For statistical tests reported, the assumption of normality was violated, so for purposes of rigour, nonparametric test versions were conducted concurrently. Differences between parametric and nonparametric tests were negligible, and did not affect interpretation of the results; therefore, nonparametric test versions are not reported. To account for multiple comparisons, the Bonferroni correction method was used for all parametric analysis. All statistical analysis was conducted using IBM SPSS v21.

3.2 Base comparisons

Firstly, 2 × 1 within-subjects analyses of variance (ANOVAs) examined baseline measures collected immediately prior to testing and immediately after. This allowed examination of whether scores changed across the testing period (e.g. due to practice effects or a familiarity with simulator flight model). ANOVAs were conducted rather than *t*-tests for purposes of consistency and to account for family wise error rates.

3.3 Awareness

The completion of the four testing trials did not significantly affect pilot's awareness ratings ($F_{1,12} = 2.87$, *ns*). Despite no main effect, it was deemed appropriate to continue to examine post hoc analysis to examine whether individual awareness factors had been susceptible to practice effects. After accounting for the required Bonferroni correction, no individual factor within pilots' awareness was identified as significantly changing as a result of practice using the HUD and simulator, desired heading ($F < 1$), rate of descent ($F < 1$), groundspeed ($F < 1$), required landing point ($F < 1$), Drift ($F < 1$) or outside environment ($F < 1$) was not significantly affected by completion of the testing phase. Pilots' awareness of power status exhibited a nonsignificant trend ($F_{1,12} = 3.98$, $p = 0.07$, *ns*).

3.4 Bedford workload and confidence

The completion of the testing period significantly affected pilots' perceived workload scores ($F_{1,12} = 4.60$, $p < .05$, $\acute{\eta}_p^2 = 0.28$); pilots' perceived workload scores decreased after participation in the testing phase (see Table 1), suggesting that practice using the simulator reduced perceived workload. However, completion of the testing phase had no significant impact on pilots' likeliness to go-around ($F_{1,12} = 1.00$, *ns*).

3.5 NASA-TLX

The completion of the four testing trials did not significantly affect pilots' NASA-TLX workload ratings ($F_{1,12} = 2.30$, *ns*). Despite no main effect, it was deemed appropriate to continue cautiously with post hoc analysis, to examine whether individual awareness factors had been susceptible to practice effects. Pilots physical load ($F_{1,12} = 1.84$, *ns*), mental workload ($F_{1,12} = 3.48$, $p = 0.09$, *ns*), temporal load ($F < 1$), effort ($F < 1$), and overall workload ($F < 1$) were not significantly affected by the testing period. Pilots' performance rating ($F_{1,12} = 11.39$, $p < 0.01$, $\acute{\eta}_p^2 = 0.49$) and frustration ($F_{1,12} = 7.63$, $p < 0.01$, $\acute{\eta}_p^2 = 0.39$), however, were significantly different between the testing periods. Pilots' performance rating and reported levels of frustration both increased after participation in the testing phase (see Table 1).

Table 1 Means and standard deviations of pilot's subjective ratings for two base measures

	Mean ± SD		*F* value
	Base		
	Prior to testing	After testing	
PLA			
Main effect	–	–	2.87
Heading	5.15 ± 2.15	5.08 ± 1.93	.05
Descent	5.15 ± 1.41	5.31 ± 1.55	.17
Groundspeed	4.46 ± 1.45	4.69 ± 1.97	.68
Power status	4.46 ± 1.51	5.15 ± 1.46	3.98
Landing	5.53 ± 1.66	5.61 ± 1.80	.03
Drift	4.54 ± 1.39	4.85 ± 2.08	.79
Environment	5.31 ± 1.38	5.46 ± 1.27	.17
PLA confidence			
Go-around	1.31 ± 0.63	1.15 ± 0.38	1.00
PLA Bedford scale			
Workload	3.77 ± 2.24	2.84 ± 1.68	4.60*
PLA NASA-TLX			
Main effect	–	–	2.30
Mental	8.69 ± 5.59	6.46 ± 4.58	3.48^{t}
Physical	6.77 ± 5.12	5.23 ± 3.24	1.84
Temporal	5.00 ± 2.61	5.31 ± 2.46	.12
Performance	12.38 ± 5.06	16.00 ± 1.96	11.39**
Effort	9.23 ± 5.26	8.54 ± 4.84	.34
Frustration	12.38 ± 5.49	15.23 ± 3.24	7.63**
OWL	54.46 ± 14.47	56.38 ± 11.40	.57

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

3.6 Role of weather and display

A series of 2 × 2 within-subjects multivariate analyses of variance (MANOVAs) were conducted to examine how weather conditions and display type impacted upon pilots' subjective situational awareness ratings, NASA-TLX scores, Bedford workload scores and landing confidence ratings. Univariate analyses of variance (ANOVAs) were conducted for further evaluation of dependant variables, alongside post hoc tests where appropriate. Post hoc analyses were also reported on nonsignificant trends ($p < 0.1$), to promote a greater understanding of the results.

3.7 Weather

Weather significantly affected pilots' awareness of desired heading ($F_{1,12} = 5.02$, $p < 0.05$, $\acute{\eta}_p^2 = 0.30$), rate of descent ($F_{1,12} = 8.32$, $p < 0.05$, $\acute{\eta}_p^2 = 0.41$), groundspeed ($F_{1,12} = 5.57$, $p < 0.05$, $\acute{\eta}_p^2 = 0.32$), power status ($F_{1,12} = 6.90$, $p < 0.05$, $\acute{\eta}_p^2 = 0.37$), required landing point ($F_{1,12} = 8.86$, $p < 0.05$, $\acute{\eta}_p^2 = 0.43$), drift ($F_{1,17} = 7.26$, $p < 0.05$, $\acute{\eta}_p^2 = 0.38$) and outside environment ($F_{1,17} = 10.19$, $p < 0.01$, $\acute{\eta}_p^2 = 0.46$). Post hoc analysis revealed that in degraded visual conditions without HUD, pilot's awareness of rate of descent groundspeed, power status, required landing point and outside environment was significantly ($p < 0.05$) lower than in clear visual conditions without HUD (see Table 2). Pilot's awareness of rate of descent, drift and desired heading was significantly ($p < 0.05$) higher in clear visual conditions with HUD than degraded visual conditions with HUD (see Table 1). In degraded visual conditions with HUD, pilots' awareness of groundspeed, power status, required landing point and outside environment was lower than in clear visual conditions with HUD (see Table 1), although such differences were not significant ($p > 0.05$). In degraded visual conditions without HUD, pilot's awareness of desired heading and drift was lower than in clear visual conditions without HUD (see Table 2), but not significantly different ($p > 0.05$).

3.8 Display

Post hoc analysis revealed pilots' awareness of desired heading ($F < 1$), rate of descent ($F < 1$), groundspeed ($F_{1,12} = 1.00$, *ns*), power status ($F < 1$), required landing ($F < 1$), drift ($F < 1$) and outside environment ($F_{1,12} = 1.04$, *ns*) were not significantly affected by display.

3.9 Weather × display

Post hoc analysis revealed pilots' awareness of desired heading ($F_{1,12} = 3.02$, *ns*), rate of descent ($F < 1$), groundspeed ($F < 1$), power status ($F < 1$), required landing ($F < 1$), drift ($F < 1$) and outside environment ($F_{1,12} = 2.88$, *ns*) were not significantly affected by interactions between weather and display.

3.10 Post-landing assessment: situation awareness

A significant main effect of weather ($F_{1,12} = 4.76$, $p < 0.05$, $\acute{\eta}_p^2 = 0.85$) was observed on situation awareness; there was, however, no main effect of display ($F < 1$) and no significant interaction between weather and display was observed ($F < 1$). Despite limited main effects, due to the small sample size and the exploratory nature of the research, it was deemed appropriate to continue with univariate follow-up procedures to examine differences in the individual-dependent variables.

3.11 Post-landing assessment: Bedford workload scale

Pilots' workload was significantly affected by the main effect of weather ($F_{1,17} = 19.85$, $p < 0.01$, $\acute{\eta}_p^2 = 0.62$). Post hoc analysis revealed that pilots' workload was significantly higher ($p < 0.05$) both with and without HUD

Table 2 Means and standard deviations of pilot's subjective ratings across two conditions of weather and display type

	Mean ± SD				*F* value		
	Clear		Fog				Weather* HUD
	No HUD	HUD	No HUD	HUD	HUD	Weather	
Post-landing assessment							
Main effect	–	–	–	–	.55	4.76*	.85
Head	5.23 ± 1.96	5.69 ± 2.10	4.77 ± 1.59	4.54 ± 1.66	.27	5.02*	3.02
Descent	5.38 ± 1.56	5.77 ± 1.48	4.46 ± 1.27	4.62 ± 1.66	.85	8.32*	.29
GS	4.69 ± 2.14	4.77 ± 2.17	3.77 ± 1.74	3.69 ± 1.89	.00	5.57*	.08
PS	5.15 ± 1.57	5.46 ± 1.51	4.31 ± 1.44	4.62 ± 1.33	.56	6.90*	.00
Landing	5.69 ± 1.38	5.46 ± 1.66	4.54 ± 1.98	4.46 ± 1.85	.16	8.86*	.06
Drift	5.15 ± 1.52	5.00 ± 1.78	4.15 ± 1.57	3.85 ± 1.57	.43	7.26*	.07
ENV	5.77 ± 1.42	5.54 ± 1.39	3.38 ± 1.85	4.23 ± 1.92	1.04	10.19**	2.88
Confidence							
GA	1.31 ± 0.85	1.23 ± 0.44	2.85 ± 1.99	3.77 ± 2.52	.89	16.32***	1.90
Bedford workload							
WL	3.31 ± 1.80	3.54 ± 1.90	6.08 ± 1.98	5.15 ± 2.12	.82	19.85***	4.02t
NASA TLX							
Main effect	–	–	–	–	.64	7.09***	2.53
Mental	6.38 ± 4.56	10.46 ± 5.22	12.69 ± 4.52	13.31 ± 4.01	3.98[t]	29.20***	6.46*
Physical	5.38 ± 3.62	6.92 ± 4.54	10.08 ± 4.13	8.54 ± 4.72	.00	32.88***	5.98*
Temp	5.08 ± 1.89	6.08 ± 2.53	10.00 ± 4.06	10.69 ± 4.63	1.09	28.32***	.07
Performance	12.62 ± 5.03	10.31 ± 6.30	9.69 ± 5.19	12.38 ± 5.06	.03	8.41**	2.81
Effort	8.15 ± 4.00	10.62 ± 4.74	13.38 ± 3.45	13.69 ± 3.22	2.20	21.94***	.93
Frustration	13.85 ± 4.76	12.62 ± 4.66	10.46 ± 4.54	8.15 ± 4.02	1.78	9.11*	.31
OWL	53.62 ± 12.88	59.31 ± 14.38	66.92 ± 14.47	64.08 ± 12.17	.38	8.49*	5.43*

* p <.05, **p < 0.01, ***p < 0.001

in degraded visual conditions than in clear visual conditions; however, this effect was much greater ($p < 0.001$) without HUD (see Table 2). No significant main effect of display was observed ($F < 1$) although a nonsignificant trend for the interaction of weather and display type was observed ($F_{1,12} = 4.02$, $p = 0.07$, *ns*). Post hoc analyses revealed pilot workload was significantly higher ($p < 0.05$) in degraded visual conditions with and without HUD than in clear visual conditions without and with HUD, respectively.

3.12 Post-landing assessment: confidence

Pilots' likeliness to go-around was significantly affected by the main effect of weather ($F_{1,17} = 16.32$, $p < 0.01$, $\acute{\eta}_p^2 = 0.58$) but not display ($F < 1$) or the interaction of the two factors ($F_{1,12} = 1.90$, *ns*). Post hoc analysis revealed pilots' likeliness to go around was significantly higher ($p < 0.05$) in degraded visual conditions, both with and without HUD, than clear visual conditions (see Table 2).

3.13 Post-landing assessment NASA-TLX

A significant main effect of weather was observed on NASA-TLX ratings ($F_{1,12} = 7.09$, $p < 0.05$, $\acute{\eta}_p^2 = 0.86$). No significant main effect of display ($F < 1$) or significant interaction effect between weather and display ($F_{1,12} = 2.53$, *ns*) were observed. Despite limited main effects, due to the small sample size and the exploratory nature of the research, it was deemed appropriate to continue with univariate follow-up procedures to examine differences in the individual-dependent variables.

3.14 Weather

Pilots' mental workload ($F_{1,12} = 29.20$, $p < 0.01$, $\acute{\eta}_p^2 = 0.71$), physical workload ($F_{1,12} = 32.88$, $p < 0.01$, $\acute{\eta}_p^2 = 0.73$), temporal workload ($F_{1,17} = 28.32$, $p < 0.01$, $\acute{\eta}_p^2 = 0.70$), performance ($F_{1,12} = 8.41$, $p < 0.05$, $\acute{\eta}_p^2 = 0.41$), effort ($F_{1,12} = 21.94$, $p < 0.01$, $\acute{\eta}_p^2 = 0.65$), frustration ($F_{1,12} = 9.11$, $p < 0.05$, $\acute{\eta}_p^2 = 0.43$) and overall workload ($F_{1,12} = 8.49$, $p < 0.05$, $\acute{\eta}_p^2 = 0.41$) were significantly affected by weather.

Post hoc analyses revealed pilots' mental load, physical load, temporal load, effort and overall workload was significantly lower ($p < 0.001$) in clear visual conditions without HUD than degraded visual conditions without HUD (see Table 2). Pilots mental load, physical load, temporal load and effort was also lower in clear visual conditions with HUD than degraded visual conditions with HUD (see Table 1), although such effects were much smaller than when comparing weather conditions without HUD ($p < 0.05$). Pilot perceived performance was significantly ($p < 0.05$) higher in clear visual conditions without HUD than degraded visual conditions without HUD; performance in degraded visual conditions without HUD was lower than degraded visual conditions with HUD (see Table 2), although such differences were not significant ($p > 0.05$). Pilot's frustration was higher in degraded visual conditions with and without HUD (see Table 2), although such difference were only significant ($p < 0.05$) in the degraded visual conditions with HUD. Pilots overall workload was lower in clear visual conditions with HUD than degraded visual conditions with HUD (see Table 2) although such difference were not significant ($p > 0.05$).

3.15 Display

Pilots' physical workload ($F < 1$), temporal workload ($F_{1,12} = 1.09$, *ns*), performance ($F_{1,12} = 1.09$, *ns*), effort ($F_{1,12} = 2.20$, *ns*), frustration ($F_{1,12} = 1.78$, *ns*) and overall workload ($F < 1$) were not significantly affected by display. Mental workload revealed a nonsignificant trend ($F_{1,12} = 3.98$, $p = 0.07$, *ns*). Post hoc analyses revealed that pilot mental workload was significantly ($p < 0.05$) higher in clear visual conditions with HUD than clear visual conditions without HUD. It was found that pilots' mental workload was higher in degraded visual conditions with HUD than degraded visual conditions without HUD although such differences were not significant ($p > 0.05$).

3.16 Weather × display

The interaction of weather and display significantly affected pilots' mental workload ($F_{1,12} = 6.45$, $p < 0.05$, $\acute{\eta}_p^2 = 0.35$), physical workload ($F_{1,12} = 5.98$, $p < 0.05$, $\acute{\eta}_p^2 = 0.31$), and overall workload ($F_{1,12} = 5.43$, $p < 0.05$, $\acute{\eta}_p^2 = 0.31$). Post hoc analyses revealed that pilots' mental workload, physical workload and overall workload was significantly ($p < 0.05$) higher in degraded visual conditions with HUD than clear visual conditions with no HUD (see Table 2). Pilots' mental workload and overall workload was higher in degraded visual conditions with no HUD than clear visual conditions with HUD (see Table 2), although such differences were not significant ($p > 0.05$). Pilots' physical workload was significantly ($p < 0.05$) higher in degraded visual conditions with no HUD than in clear visual conditions with no HUD (see Table 2). Pilots' temporal workload ($F < 1$), perceived performance ($F < 1$), effort ($F < 1$) and frustration ($F < 1$) were not significantly affected by weather and display interactions.

4 Discussion

Results indicate that the HUD led to significant reductions in pilot perceived workload during degraded compared to clear visual conditions, although no differences were observed in pilots' situation awareness. This suggested that although the HUD did not improve pilots' situation awareness, a similar level of awareness could be reached more easily. This finding offers partial support for hypothesis 1, in relation to workload, but partly rejecting it, in relation to situation awareness. On potential explanation of this finding, however, is that pilot's situation awareness had already reached an acceptable level when operating in clear visual conditions, hence could not be improved upon further. Importantly, operating within the degraded visual environment did not impair pilots' situation awareness when they had access to the HUD; indeed, participants recorded situation awareness did not significantly differ when flying in the degraded visual environment with the HUD compared to recorded situation awareness when pilots flew without the HUD in clear visual conditions. This offers support for hypothesis 2. Limited differences in pilot situation awareness with or without the HUD were observed in clear visual conditions, offering support for hypothesis 3. However, pilot workload was higher when using the HUD in clear visual conditions. Results shall now be discussed more specifically to evaluate the usefulness of the HUD concept.

In the current study, no significant differences in pilot situation awareness were observed when using the HUD in clear visual conditions compared to no HUD. This indicates that the HUD did not have a detrimental impact upon flight performance during clear visual conditions. These results are consistent with previous work (Stanton et al. 2016a, b) and offer further support for the development of a HUD that is continuously usable during both clear and degraded visual conditions. Pilots' workload when using the HUD in clear visual conditions, compared to flight in clear visual conditions with no HUD, did not significantly differ, but was higher. This contrasts previous work (Stanton et al. 2016a, b), whereby the trend was for workload to decrease when using the HUD, even in clear conditions. The displays used within the current research study were, however, an evolution of those used by Stanton et al. (2016a, b), suggesting that not all changes had had a positive impact. This finding emphasises that HUD technologies must be refined in order to be usable and supportive to pilots' needs.

The finding that perceived workload increased when the HUD was available in clear visual conditions is consistent with Prinzel Iii et al. (2004) who noted that the use of internal cockpit cues induced greater workload than external environmental cues. That participants' workload increased in the clear flying conditions when they had access to the HUD is not necessarily a negative outcome, however, as no evidence of decreased flying performance was observed as a result of the presence of the HUD. This suggests that the increase in workload was within the manageable confines, without the need to use more error prone heuristics (Harris 2011; Klein 1997).

That situation awareness did not alter between clear and degraded visual conditions was not anticipated, primarily as visual cues are central in informing situation awareness (Doehler et al. 2009). It would be anticipated that the lack of clear visual cues within the degraded visual condition would therefore impede pilots' situation awareness. This was not, however, the case, with no clear indications that situation awareness was impeded. This finding, however, may be partially attributed to the expert nature of the participants who took part within the research study and the task. All participants were qualified rotary-wing pilots with a mean of 3415 h flown and had all flown within a year of participation. The flight task used within this study can also be considered routine and may have not been demanding enough to demonstrate changes in situation awareness, especially when supported by the available on-board technologies (Stanton et al. 2010). The reduction of perceived workload within the degraded visual condition, compared to clear visual condition, suggests, however, that the HUD was beneficial to the pilots.

Despite no main effect of participant situation awareness being observed between clear and degraded visual conditions, the degraded visual conditions significantly reduced pilot's awareness of rate of descent, groundspeed, power status, landing site, drift and the outside environment, consistent with previous research (Foyle et al. 1992). The largest observed decrease was awareness of the outside environment. The observed decrease of pilots' awareness in degraded visual environments was compounded by a significant increase in pilots' workload and an increase in the likelihood of a go-around being performed. These results offer validation for the experimental manipulation in that visual conditions were degraded to an extent that a reliance on external visual cues could not be maintained. Similar to previous work (Stanton et al. 2016a, b), the largest differences between workload and awareness of the external environment were observed when comparing pilot performance with and without the HUD between clear and degraded visual conditions (see Table 2). This offers excellent conditions to examine whether the HUD can, to some extent, negate the need for a change in flight style in degraded visual conditions.

In degraded visual conditions, the HUD did not significantly impact upon pilots' awareness of all flight parameters when compared to flight with traditional cockpit controls in clear visual conditions (see Table 2). The awareness ratings were markedly similar, indicating the HUD concept allowed participants to maintain their level of awareness in the degraded visual condition. Despite no improvements in awareness, significant decreases in overall pilot workload (NASA-TLX) were observed. A breakdown of the NASA-TLX sub-scales revealed that the mental workload of pilots was slightly higher with the HUD but physical workload was significantly lower. This suggests that whilst the HUD increased the cognitive demands for the task, the information was presented in a way which was within easy reach and highly accessible. The temporal awareness and effort of pilots were almost identical (see Table 2) when comparing using the HUD with not using the HUD in degraded visual conditions. These results seem to indicate that whilst the HUD is generally having a positive impact upon workload, it is not reducing cognitive demand. In the current study, the perception of time was similar in degraded visual conditions with and without the HUD, indicating cognitive load between these conditions was comparable. The significant decrease in general workload indicates that the information being presented to pilots is being processed more intuitively than traditional cockpit displays. Presenting 2D traditional flight information in the HUD allowed pilots to fly 'eyes out' without a need for continuous shifts of attention to traditional technologies inside the cockpit, potentially explaining the observed reduction in physical load.

A further point of discussion is the comparison of the base line conditions flown immediately before the experimental conditions and immediately following. The main purpose of these scenarios was to assess whether practice effects, as a consequence of participants' exposure to the simulator and flight model, influenced results. No significant effects were found for pilot's awareness of heading, descent groundspeed, drift, outside environment and landing site. This finding indicates that familiarisation with the simulator (flight model and technologies) across the four experimental trials did not improve performance after initial familiarisation training. This suggests that the initial familiarisation period and training was adequate for pilots and that experience gained throughout the study should not impact upon the results. Pilot awareness of power status exhibited a non-significant trend, showing an increase over baseline flights following the experimental conditions. This implies that experience with the simulator facilitated pilot awareness of power status. It may be that pilots required further initial training concerning how to obtain and process information concerning power status. Alternatively, this finding can be

seen as indicative that the way power information is presented within the symbology requires further refinement.

Throughout the study perceived workload, as measure by the Bedford scale and NASA-TLX mental component, decreased, whilst pilots' perceived performance, as measured by NASA-TLX, significantly increased. This finding suggests that by the end of the study pilots believed they were performing to higher standard, but did not have to work as hard to achieve these goals. Such differences are, however, to be expected, during the initial flights pilots may have been experiencing normal anxiety resulting from participation in a formal experiment (Oswald et al. 2014). It is also possible that more experience with the flight model and technologies would reduce workload. The reduction in workload resulting from experience in the simulator should not, however, be considered problematic for a number of reasons. Firstly, such improvements did not impact upon situation awareness. Secondly, the presentation order of scenarios was counterbalanced between participants. Thirdly, some results reveal significant increases in workload, indicating that improvements based on experience are minor and having minimal impact upon the experimental manipulation comparisons. Interestingly, pilots' frustration significantly increased when comparing baseline flight before and after the experimental manipulations. This indicates that by the end of the testing period, pilot's frustration was growing. This is perhaps due to being asked to fly in conditions that would not normally be encountered, degraded visual, or simply due to spending a long period in the simulator, particularly with the extra base flight scenarios. Rising level of frustration did not, however, appear to negatively impact pilot performance. One factor that may have influenced pilots rising level of frustration was the level of simulator fidelity. Although the simulation sought to provide pilots with realistic views and controls, they were not actively flying within a real helicopter cockpit. It has been long argued that simulation fidelity can impact performance and task rating (Rehmann et al. 1995). The rising level of frustration could therefore be an artefact of the moderate fidelity not perfectly aligning with what the expert users would expect.

This study has highlighted the value of a HUD to pilots when operating within degraded visual environments. Addressing how information should be presented to pilots is an essential, yet frequently overlooked aspect. As previously suggested, an overly cluttered HUD can be detrimental to both pilot task performance and situation awareness, particularly when task irrelevant information is presented in demanding situations (Yeh et al. 2003). Access to a HUD can, however, facilitate task performance by reducing the visual scan required but also aiding in the integration of different information forms (Ververs and Wickens 1998). Understanding and de-cluttering a HUD display, so that only task relevant information is displayed is a continuing trend in aviation research, both in rotary-wing and fixed-wing aircraft. Demonstrating the value of adaptive symbology in fixed-wing aircraft, Richards et al. (2016) showed that the presentation of only task relevant information via a HUD leads to significant reductions in pilots perceived mental demand and effort, whilst simultaneously increasing pilot performance as measured by deviation from centre line during a landing approach. Undoubtedly addressing the challenge of what, and when, information should be presented on a HUD is a significant piece of work, however, and this topic must remain at the forefront of research.

A limitation encountered with the study was revealed when considering participants comments to the researcher team. Pilots' suggested that the flight path flown and recommended by the HUD was not one that would be commonly encountered in everyday flight operations; rather it was what might be expected when landing at an unprepared site. It is possible that the recommended flight profile may have negatively impacted situation awareness, particularly during degraded visual conditions when the demand placed on pilots was already high. However, as the same flight profile was used in all conditions, such reasoning cannot solely be responsible for the lack of observed situation awareness improvements.

5 Conclusions

Rotary-wing aircraft offers civil aviation, the potential to play an essential role in future personal transport needs. However, their vulnerability to constraints including flying conditions and weather currently restricts these craft reaching their full potential. By maturing available cockpit technology, including synthetic vision systems, many of these obstacles can be overcome, improving current service provision and supporting future growth. Results from the current study echo previous work demonstrating that flight in degraded visual environments is great challenge, increasing pilot workload and reducing situation awareness. The current study, however, also indicated that these challenges could be greatly reduced when pilots had access to a HUD. With access to a HUD, pilots' levels of workload and situation awareness are not significantly different under degraded visual conditions compared to those recorded during clear flight. This result demonstrates that access to synthetic vision technology, specifically a HUD, reduces the difficulties associated with flying in degraded visual environments.

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