Head-Up Displays Assist Helicopter Pilots Landing

in Degraded Visual Environments

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Abstract

Civilian rotary-wing aircraft pilots typically rely on visual information from the external environment to guide flight, but are increasingly required to operate in degraded visual environments. The current study evaluated the impact of a Head-Up Display (HUD) upon pilot performance, perceived situation awareness and workload. A 2 x 2 repeated measures design required qualified rotary-wing pilots *(N=6)* to fly in clear and degraded visual conditions both with and without the HUD. In degraded visual conditions, the HUD significantly improved pilot perceived situation awareness whilst simultaneously reducing workload. Objective flight technical performance data offered preliminary support for a positive change in pilot behaviour when using the HUD in degraded visual conditions.

**Key words:** Rotary-wing, Head-Up Display, Situation Awareness, Workload

Introduction

The operational benefits of helicopters (e.g. low altitude flight, vertical take-off/landing) facilitate flight to remote locations, including unimproved landing sites without aviation-related ground infrastructure (Baker, Shanahan, Haaland, Brady & Li, 2011; Swail & Jennings, 1999; Grissom, Thomas & James, 2006). Despite fewer flight hours, accident rates of rotary-wing aircraft are significantly greater than for fixed-wing aircraft (Doehler, Lüken, & Lantzsch, 2009). Whilst the mechanical complexity and different pilot-skill requirements of rotary-wing aircraft can account for a proportion of this discrepancy, it cannot explain such a large difference in isolation. One significant contributing factor to rotary-wing accidents is degraded visibility (Baker et al., 2011). Baker et al., (2011), explored 178 reported rotary-wing accidents which occurred in the Gulf of Mexico between 1983 and 2009 and found that 16 % were directly attributable to poor weather and degraded visual conditions. Furthermore, it was found that accidents occurring within such conditions accounted for the highest proportion of fatalities (40%). Importantly, many of these fatalities can be considered a direct consequence of low altitude flight over water, due to conditions (Taber & McGarr, 2013). Poor weather and degraded visual conditions not only increase the complexity of a rotary-wing operations, but also increase pilots workload, resulting in a potential deterioration in the cognitive capacity of the pilot (Shappell & Wiegmann, 2004) and subsequently, due to an increased level of stress, increasing the potential for errors to occur (Sneddon, Mearns & Flin, 2013).

The operational benefits of helicopters have driven an increased demand for their use in degraded visual conditions in a civilian setting (Baker et al., 2011; The British Helicopter Association, 2014). A Human Factors analysis of rotary-wing search and rescue operations in degraded visual conditions (Swail & Jennings, 1999) indicated that assisting pilots with required descents below minimum descent altitude, facilitating search operations and the capacity to transition to a low-altitude hover were key task elements within rotary wing operations. Critically, these tasks were deemed impossible to perform in degraded visual conditions without advanced technological assistance including an augmented visual scene, such as provided by a heads up display (HUD), presented to the pilot alongside aircraft instrument symbology (Swail & Jennings, 1999).

The aim of the current work is to develop and test technologies that might facilitate rotary-wing flight in degraded visual conditions in order to increase the safe operation capabilities of such aircraft.

A Brief Overview of Situation Awareness

The principle of distributed situation awareness suggests that appropriate information/knowledge relating to the task and the environment is held both by individuals and technological agents within a system (Stanton et al., 2006; Salmon, et al., 2008, Salmon & Stanton, 2013). From a systems perspective, during flight, situation awareness is distributed across the cockpit. Situation awareness should be viewed as a cyclical, parallel and dynamic activity that changes as the situation develops (Smith & Hancock, 1995; Harris, 2011; Salmon, et al., 2009). Pilot situation awareness is more than a mere state of knowledge; it is the construction of a mental model of a situation based on the extraction of relevant perceptual information (sampling) from the environment (e.g. external visual cues and internal cockpit readings) and prior experience that can be driven in both a bottom-up and top-down manner (Plant & Stanton, 2012). Pre-existing schemata facilitate pilot situation awareness by efficiently organising the perception and use of information to reduce cognitive load (Plant & Stanton, 2012; Hutchins, 1995). In this regard, 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, Salmon, Walker & Jenkins, 2010; Harris, 2011). Situation awareness may therefore be distributed across multiple agents, both human and non-human technology, within a system (Stanton, Salmon, & Walker, 2014). Examples of distributed situation awareness can be seen within a variety of social-technical systems, such as submarine operations (Stanton, 2014) and fixed-wing aircraft operations (Stanton, Harris, & Starr, 2016), however limited applied studies with rotary-craft are available, a gap this study seeks to begin to address.

To maintain situation awareness pilots typically use at least three external visual reference points to monitor altitude and position, whilst also periodically scanning the instrument panel (see Squirrel HT1/2 flying guide instructions; Foyle, Kaiser & Johnson, 1992). The instrument scanning behaviour of pilots’ supports the notion of confirmatory information ‘checking’, that is, more time is dedicated to the scanning task should an un-expected measure be observed (Wickens, 2002; Bellenkes, Wickens & Kramer 1997; Kasarskis, Stehwien, Hickox, Aretz, & Wickens, 2001). In clear visual conditions, pilots typically fly proactively, routinely sampling technical flight parameters in relation to the anticipated dynamics of the aircraft (Snow & Moroze, 1999; Prinzel III, et al., 2004). When flying at low altitude, visual information (e.g. physical geometry of terrain) from the outside world greatly informs pilot situation awareness (Doehler et al., 2009; Foyle et al., 1992; Nasciemento, Majumdar, & Ochieng, 2013).

Cognitive Workload

In degraded visual conditions, pilots cannot rely on visual information from the external environment to fly in an anticipatory fashion (Doehler et al., 2009). A shift is made to reactionary control, using cockpit instrumentation to generate mental models and facilitate appropriate schemata selection rather than to confirm such processes, potentially increasing cognitive demand (Snow & French, 2002; Harris, 2011; Klein, 1997; Wickens, 2002; Prinzel III, et al., 2004). Cognitive demand is defined as the amount of mental effort an operator must expend on a task, relative to available resources, or the cost of information processing in terms of performing a given task (Harris, 2011; Farmer & Brownson, 2003). Future cockpit technology should optimise workload, and improve situation awareness, particularly in degraded visual conditions (Harris, 2011; Melzer, 2012). The current work aimed to develop a cockpit technology that facilitates pilot situation awareness of external cues and technical flight parameters, whilst simultaneously reducing cognitive load.

Heads-up display (HUD) and conformal symbology

A heads-up display (HUD), within a helicopter operation context, is a glass mounted panel in the pilots near visual field that displays flight information, typically 2D traditional flight references (e.g. airspeed) and may potentially present a 3D (conformal) graphical representation of the external environment within an augmented display (Swail & Jennings, 1999; Thomas & Wickens, 2004; Prinzel III et al., 2004). A HUD allows a pilot to fly ‘eyes out’ rather than switching attention to head-down displays (HDD) inside the cockpit. Presentation of information in a HUD can optimise workload and increase situation awareness as there is less dissociation between the pilots’ task of flying and navigating (Snow & Reising, 1999; Ververs & Wickens, 1998; Snow & French, 2002; Heiligers, Van Holten & Mulder, 2009). The presentation of synthetic environmental information in a HUD compared to a HDD has been shown to improve pilot performance (Prinzel III et al., 2004). Conformal symbology leads to faster detection response to changes within the symbology and improved flight-path tracking accuracy (Fadden, Ververs & Wickens, 1998; Snow & French, 2002). Real flight studies found that conformal symbology provides improved path control and situation awareness in terrain-challenged operating environments (Prinzel III, et al., 2002). The current work developed and assessed the usefulness of a HUD with 2D flight symbology and 3D perspective-view symbology. The use of such technologies is widespread in fixed-wing aircraft and the military domain but is very rare in civilian rotary-wing aircraft (Doehler et al., 2009; Theunissen, Koeners, Rademaker, Jinkins, & Etherington, 2005).

HUDs have, however, been demonstrated to degrade the detection of unexpected events due to attentional tunnelling (Wickens & Alexander, 2009; Fadden, Ververs & Wickens, 1998). This occurs when attention is allocated to a particular channel of information for longer than is optimal, resulting in the neglecting of other relevant information (Wickens & Alexander, 2009; Snow & French, 2002). A cluttered HUD can be detrimental to pilot situation awareness, particularly when task irrelevant information is presented in demanding situations (Yeh, Merlo, Wickens & Brandenburg, 2003). To optimize the benefits of a HUD, designers must preserve the most useful and unambiguous visual cues pilots naturally use so that information is processed intuitively (Foyle, Kaiser & Johnson, 1992; Harris, 2011; Prinzel III et al., 2004; Ververs, & Wickens, 1998; Klein, 1997). The current work also aimed to assess the usefulness of a HUD in clear visual flying conditions, as the presentation of flight information in a HUD may also be beneficial in clear visual conditions (Ververs & Wickens, 1998). This study presents an initial examination of a potential HUD design, developed under SME guidance, using ergonomic methods (Stanton, Plant, Roberts, Harvey & Thomas, 2016)

Based on previous literature, the following hypotheses were generated:-

1. In degraded visual conditions, participants will record an increase in workload and a decrease in situation awareness (Sneddon, Mearns & Flin, 2013; Shappell & Wiegmann, 2004).
2. Access to a HUD will reduce the impact of the degraded visual conditions on workload and situation awareness (Prinzel III et al., 2004).
3. Access to a HUD will facilitate pilots’ situation awareness in clear visual conditions (Ververs & Wickens, 1998).

Method

Design

The study employed a 2 x 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 conditions were presented was counterbalanced between participants to minimise potential order effects.

Participants

Six male participants aged 37 – 65 years (*M=* 51.00*, SD=* 10.29) were recruited using advertisement posters disseminated at local airfields alongside recommendations from acquaintances of pilots who had previously participated. All Participants were qualified rotary-wing pilots with varying rotary-wing flight hours flown, ranging from 108 – 8300 hours (*M=* 3804*, SD=* 3468). Ethical permission for this study was granted by the Research Ethics Committee at the University of Southampton (ERGO 4032).

Equipment and Materials

*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 large screens. This setup provided a 140o 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 on Prepar3D (previously Microsoft flight simulator software). The flight scenario was located over a runway at the Norfolk naval base, Virginia, USA, using the Bell 206 flight model. The Prepar3D software is highly customisable and allowed the required weather conditions to be simulated. In the clear- sky condition the clear weather setting was selected and in the degraded visibility condition the highest fog setting was used. The fog setting created an environment with thick advection fog that reduced pilot visibility to 0.5km.

*Head down Display -* The Head down display (HDD) was displayed to the pilots on the outer right multi-function display unit in the simulator. This was available to the pilots in 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 engine torque vertical scale indicator.

*Head up Display -* The development of the HUD was part of a larger research project in which the concept was designed with the aid of Cognitive Work Analysis (see Stanton & Plant, 2010; 2011; Stanton, Plant, Roberts, Harvey & Thomas, 2016). The requirement was that the HUD would be capable of assisting the pilot with performing approach and landing in a degraded visual environment. In line with potential future cockpit capabilities, the HUD was developed in a full-colour system with an extended field-of-view (e.g. future windshield displays). To assist with the landing task the HUD included a flight path vector, which represented the point on the ground that would be hit if velocity was maintained (see figure 1, #1). Perspective view augmented reality ‘trees’ were located in a fixed position at the landing site starting at 150 feet, providing a visual reference point when landing (see figure 1, #2). The arrows on the trees moved in accordance to aircraft’s altitude, to provide intuitive information concerning height and rate of descent (see Figure 1, #3). The HUD concept was created using GL Studio. 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 an open source 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 (see Figure 1).

**INSERT FIGURE 1 HERE**

*Flight technical performance data* - The frame rate of the simulation software was set to range between 10 and 20 frames-per-second. The simulator was set to record a variety of flight technical performance data (e.g. vertical speed, altitude, torque) at a rate of 5 Hz. Pilots were not provided with any guidance concerning the landing approach that should be taken (e.g. shallow, standard or steep), therefore the flight technical performance data can offer insight into the flight profile adopted within differing conditions. The depth of this data however is limited by the sample size within the current study. This is compounded by inherent differences in how rotary-wing pilots fly, which varies considerably more than would be encountered when considering fixed-wing pilots.

A discussion with Subject Matter Experts (SMEs) at a leading aircraft manufacturer was a source of data that allowed the determination of what parameters might be used to objectively evaluate the HUD. It was proposed that optimal flight profiles should be ‘smooth’ with gradual decreases in altitude and vertical speed, promoting a fast descent in a safe fashion. To evaluate this, flight profiles of all participants in all conditions were averaged and plotted. The time it took for pilots to reach ‘pre-set flight gates’ were examined. The gates were set at 800ft, 600ft, 400ft, 200ft, 100ft, 50ft and ground, but pilots were not informed of the ‘flight gates’. SMEs agreed that these ‘gates’ represented landmark points at which parameter checks informing rate of descent would be made to allow prospective flight (i.e. allow adjustments to be made if the rate of descent was deemed inappropriate). To examine how pilot behaviour influenced flight profiles in a transactional fashion, the time taken by pilots to reach flight gates accumulatively was assessed.

*Questionnaires* - Two 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 questionnaire was developed by SMEs at a leading aircraft manufacturer, and was specifically designed to examine the situation awareness of rotary wing pilots (Stanton et al., 2016). The questionnaire asked participants to rate their awareness of various flight parameters (e.g. desired heading, desired rate of descent) from 1 (low) to 7 (high). The questionnaire therefore offered a measure of perceived situational awareness. The post-landing assessment questionnaire also asked for a rating of pilot inclination to perform a go-around manoeuvre from 1 (not likely) to 7 (very likely).

The Bedford Workload Rating Scale (Roscoe & Ellis, 1990) is a uni-dimensional mental workload assessment technique developed to assess pilot workload via an assessment of spare capacity. Participants followed a decision tree to derive a workload rating for the task under analysis (Stanton, et al., 2013). A scale of 1 (low workload –workload insignificant) to 10 (high workload – task abandoned) was used.

Procedure

Participants were briefed about the study and asked to complete a consent form and demographic questionnaire. Participants were then given an initial familiarisation session with the simulator. Participants were then familiarised with the HUD in a talk through provided by the software developer to explain each instrument and the conformal symbology. Participants were then given time to practice flying with the HUD. The familiarisation session lasted approximately 25 minutes. The participants then flew each of the four experimental conditions (clear, clear + HUD, degraded or degraded + HUD). For each condition participants began 5nm out to sea and were instructed to land on the runway, which was visible in the clear sky conditions. In the degraded visual environment conditions, pilots were provided with a heading and precision approach path indicators but no other tools (e.g. radio navigation). Participants were instructed to fly to the runway and land the aircraft. In the degraded visual environment only condition a 15-minute 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 post-landing assessment questionnaire and Bedford workload questionnaire were administered. 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.

Results

Data Analysis

The study was a preliminary assessment of a HUD concept, which required expert participants with limited time availability (experienced rotary-wing pilots) as such the sample size was limited (Plant & Stanton, 2016). Due to the exploratory nature of the research it was deemed appropriate to continue with statistical analysis with caution. Firstly, a series of 2 x 2 within-subjects univariate analyses of variance (ANOVAs) were conducted to examine how weather conditions and display type impacted upon pilot’s subjective situation awareness, Bedford workload, landing confidence ratings and flight technical performance data. Post hoc analyses were conducted on significant results.

It should be noted that as a consequence of the limited sample size, the data was not normally distributed; however, the parametric tests used here have been demonstrated to be robust to violations of such assumptions (see, for example, Donaldson, 1966; Keselman, Algina & Kowlchuk, 2002), although caution is warranted when interpreting the results. For the purposes of rigour, however, non-parametric test versions were conducted in all cases where such assumptions were violated. Differences between the parametric and non-parametric tests were negligible, and did not affect interpretation of the results; as such non-parametric tests are not reported. To account for multiple comparisons the bonferroni correction method was used for all parametric analysis.

Subjective Metrics

Pilots’ subjective rating of perceived situation awareness and workload are presented in Table 1. It can be seen from Table 1. that there are indications that perceived situation awareness was greater with the HUD and workload was typically reduced.

**INSERT TABLE 1 HERE**

Effect of Weather on Perceived Situation Awareness

Weather significantly affected pilots perceived awareness of the outside environment (*F*1, 5 = 7.17, *p* < .05, ήp2 = .59). Post hoc analysis revealed pilots perceived awareness of the outside environment was significantly lower (*p* < .05) during degraded visual conditions with no HUD than clear visual conditions with no HUD.

Effect of Display on Perceived Situation Awareness

The display type significantly affected pilots’ perceived awareness of desired heading (*F*1, 5 =11.79, *p* < .05, ήp2 = .70), rate of descent (*F*1, 5 = 22.23, *p* < .01, ήp2 = .82) and groundspeed (*F*1, 5 =30.94, *p* < .01, ήp2 = .86). Post hoc analysis revealed pilot perceived awareness of desired heading and groundspeed was significantly greater (*p* <.05) with the HUD, both in clear and degraded visual conditions (see Table 1).

Interaction of Display\*Weather on Perceived Situation Awareness

A significant interaction of weather and display on pilots perceived awareness of required landing point was observed (*F*1, 5 = 20.86, *p* < .01, ήp2 = .81*)*. Examination of the means suggest that the HUD significantly improved participants awareness of the landing point in degraded visual conditions. Post hoc analyses revealed pilot perceived awareness of ground speed and the outside environment was significantly (*p* < .05) higher in clear visual conditions with the HUD than degraded visual conditions without the HUD. Pilot perceived awareness of groundspeed is significantly (*p* < .05) higher in degraded visual conditions with the HUD than in clear visual conditions without the HUD.

Confidence

Weather significantly affected pilots’ inclination to go around (*F*1, 5 = 8.28, *p* < .05, *ήp2* = .62). Post hoc analyses revealed a pilot’s inclination to go around was significantly greater (*p* < .05) in degraded visual conditions than clear visual conditions both with and without the HUD (see Table 1).

Bedford Workload Scale

Weather (*F*1, 5 =7.74, *p* < .05, ήp2 = .61) and display type (*F*1, 5 = 13.97, *p* < .05, ήp2 = .74) significantly affected pilot workload. Pilots workload was significantly (*p* < .05) higher in degraded visual conditions than clear visual conditions both with and without the HUD (see Table 1). Pilots workload was significantly (*p* < .05) greater in degraded visual conditions without the HUD than degraded visual conditions with the HUD. These findings suggest that although flying in degraded visual conditions did increase, pilot workload, the HUD reduced the size of the workload increase.

Objective Flight Performance

Data concerning pilots’ objective performance was captured and is presented in Table 2. Clear differences can be seen in the flight profiles pilots adopted as a consequence of both the weather and having access to the HUD.

**INSERT TABLE 2 HERE**

Accumulated Flight Time

Weather significantly affected pilots total flight time (*F*1, 5 = 7.52, *p* < .05, ήp2 = .60) and time taken for pilots to reach the descent gates (800ft (*F*1, 5 = 6.52, *p* < .05, ήp2 = .54), 600ft (*F*1, 5 = 9.57, *p* < .05, ήp2 = .70), 400ft (*F*1, 5 = 7.29, *p* < .05, ήp2 = .58). 200ft (*F*1, 5 = 6.75, *p* < .05, ήp2 = .55), 100ft (*F*1, 5 = 8.26, *p* < .05, ήp2 = .64) and 50ft (*F*1, 5 = 8.57, *p* < .05, ήp2 = .65)). Post hoc analysis revealed pilots total flight time and time to reach 800ft, 600ft, 400ft, 200ft, 100ft and 50ft was significantly longer (*p* <.05) during degraded visual conditions without the HUD than clear visual conditions without the HUD (see Table 2 and Figures 3 and 4). No significant (*p* >.05) difference in the time taken by pilots to reach any flight gate was observed when comparing the HUD in Clear conditions to the HUD in degraded visual conditions.

**INSERT FIGURE 2 & 3 HERE**

Flight gate differences

The time taken for pilots to reach each decent flight gate was significantly affected by display type (600ft (*F*1, 5 = 8.19, *p* < .05, ήp2 = .63), 400ft (*F*1, 5 = 8.95, *p* < .05, ήp2 = .67), 200ft (*F*1, 5 = 6.39, *p* < .05, ήp2 = .53), 100ft (*F*1, 5 = 11.38, *p* < .05, ήp2 = .77) and 50ft (*F*1, 5 = 7.34, *p* < .05, ήp2 = .59)). Post hoc analysis revealed pilots took significantly longer to reach 600ft in degraded visual conditions without the HUD than in degraded visual conditions with the HUD (*p* < .05) (see Table 2 and Figures 3 and 4).

Weather significantly affected the time it took pilots to fly between 200ft to 100ft (*F*1, 5 = 8.91, *p* < .05, ήp2 = .67). Post hoc analysis revealed that pilots took significantly longer (*p* < .05) to fly between 200ft and 100ft in degraded visual conditions without the HUD than clear visual conditions without the HUD (see Table 2 and Figures 3 and 4). Post hoc analysis also revealed that pilots were significantly (*p* < .05) faster flying between 400ft and 200ft in degraded visual conditions with the HUD than in degraded visual conditions without the HUD. Pilots were significantly (*p* <.05) faster flying between 200ft and 100ft in degraded visual conditions with the HUD than degraded visual conditions without the HUD. The addition of the HUD allowed pilots to descend at greater speed than possible without the HUD.

Discussion

Results indicated that the provision of the novel HUD display led to significant improvements in pilot perceived situation awareness and a reduction in pilot workload. Such improvements were most prominent when considering the effect of the HUD within the different visual conditions. Overall, there were no differences in pilot workload or perceived situation awareness with or without the HUD in clear visual conditions but significant differences in degraded visual conditions. In summary, results indicated that the HUD display improved rotary-wing pilots perceived situation awareness in degraded visual conditions, without negatively impacting flight performance during clear visual conditions.

Flight in degraded visual conditions significantly reduced pilot’s perceived awareness of the outside environment, increased workload and increased pilot inclination to perform a go-around. In degraded visual conditions, pilots are required to rely on cockpit instrumentation rather than external visual cues; the cognitive cost of which is often associated with increases in cognitive workload (Doehler et al., 2009; Prinzel III et al., 2004). The largest differences between workload and perceived awareness of the external environment were observed when comparing pilot performance without the HUD in clear and degraded visual conditions (see Table 1). This supports previous work which suggests that pilot’s flight style changes within degraded visual conditions such that cockpit instrumentation was used to generate mental models and appropriate schemata selection rather than to confirm such processes (Snow & French 2002; Harris, 2011, Klein, 1997; Wickens, 2002; Bellenkes et al., 1997).

In degraded visual conditions pilot ratings of their awareness of all flight parameters (except power) significantly increased when the HUD was used. Awareness of obstacles at the destination, sufficiency of visual cues for approach, stability of visual cues and sufficiency of visual aids for landing are primary performance factors for pilots during flight (Nasciemento et al., 2013). The HUD used displayed a conformal perspective view synthetic representation of the outside terrain to pilots. The improvements in pilots’ rated perceived awareness of desired heading, rate of descent, groundspeed, landing point, and the outside environment indicated that in degraded visual conditions the HUD provided sufficient external visual cues for flight.

The current HUD was designed to preserve the visual cues that pilots use in order to facilitate information processing, based on SME expertise (Stanton & Plant, 2010; 2011; Stanton, et al., 2016), promoting distributed situation awareness. The observed decrease in workload suggests that the information presented to pilots was intuitive, as the requirement for the recoding of information was reduced (Foyle et al., 1992; Harris, 2011; Prinzel III et al., 2004; Ververs, & Wickens, 1998; Klein, 1997). 2D traditional flight information was also presented to pilots in the HUD; presenting information in such a manner allowed pilots to fly ‘eyes out’ without the need to continually shift attention to traditional technologies inside the cockpit. The ability to access flight information without having to make gross redirections of visual gaze has been demonstrated to decrease workload (Snow & French 2002). The current results support previous work demonstrating that the presentation of information in a HUD does not require the diverting of cognitive resources into cockpit instrumentation, leading to reduced workload and increased situation awareness (Snow & Reising; 1999; Ververs & Wickens, 1998).

The current HUD was designed for use in both clear and degraded visual conditions. Previous research has indicated that an overly cluttered HUD or the presentation of irrelevant information can negatively impact upon workload, situation awareness and flight performance (Yeh et al., 2003). In the current study, no significant differences in pilot perceived situation awareness were observed when using the HUD in clear visual conditions (compared to no HUD). This indicated that the HUD did not have a detrimental impact upon flight performance during clear visual conditions. Pilot perceived awareness of desired heading, rate of descent, groundspeed and the outside environment substantially improved, which indicated that access to the HUD benefited flight in clear conditions (see Table 1). This supports previous research indicating that the presentation of intuitive flight information via a HUD facilitates integration of different information forms (Ververs & Wickens, 1998).

The time taken to reach each checkpoint and the total time taken by pilots to land the aircraft was significantly longer in degraded visual conditions than in clear visual conditions. This suggested that reduced visual conditions negatively impacted upon flight performance throughout the descent. The longest times taken by pilots to reach gates were in degraded visual conditions with no HUD (see Table 2; Figures 3 & 4). This data should be interpreted with caution however, as a faster flight path does not necessarily mean a safer or more efficient flight path. Nevertheless, the time taken by pilots to reach flight gates at 600ft – 50ft was significantly quicker with the HUD than without the HUD in both clear and degraded visual conditions (see Table 2). The rate of descent for all conditions (except degraded without HUD) was similar from 800ft which indicated that the HUD had a positive influence on pilot behaviour, particularly when compared to the steep descent of pilots in degraded visual conditions without HUD (see Figure 3). However, the most direct route to the landing site was still taken in clear visual conditions without HUD (see Figure 2). This indicated that the current HUD design requires improvement in terms of promoting ideal navigation strategies.

Weather significantly impacted the time pilots took to fly between 200 - 100ft and 100 – 50ft, these phases of the descent took longer in degraded visual conditions (see Table 2 and Figures 3 and 4). At such altitudes pilots became more aware of potential obstacles as they looked for visual references on the ground. The time taken by pilots to fly between the flight gates was differentially affected by having the HUD in degraded visual conditions. It was not clear what such results indicate, particularly as pilots took longer to descend from 50 feet to ground with the HUD than without the HUD in degraded visual conditions but were much faster with the HUD than without the HUD in clear visual conditions (see Table 2). The HUD may have provided a supportive framework that allowed pilots to continue to fly reactively, but in a more controlled fashion. The results offered support for a change in the flight behaviours of pilots due to the HUD, which, when interpreted alongside the subjective ratings indicated a positive influence, although the precise strategies of using the HUD might be different in degraded compared to clear visual conditions. This should be considered in future HUD designs and research projects.

A primary limitation of the current study was a small sample size. Future studies should aim to recruit a greater number of participants, although recruitment of skilled pilots is a challenging pursuit. Perceived awareness of rate of descent and drift were not significantly improved with the HUD (in degraded or clear visual conditions). This was not surprising as the current HUD design focused upon creating a landing site that was easy to see using visual cues and provide intuitive landing aids (i.e. 3D synthetic trees). Research has demonstrated that Highway-In-The-Sky concepts lead to increased maintenance of lateral and vertical flight path awareness (Williams, et al., 2001). A Highway-In-The-Sky was not displayed in the current HUD design, however inclusion of such a concept in future HUD designs may improve pilot awareness of drift and rate of descent.

Conclusions

The operational benefits of helicopters are increasing demand for their use in a civilian setting, including for flight in degraded visual conditions (Stanton, Plant, Roberts, Harvey & Thomas, 2016). There is clear a demand for the development of future rotary-wing cockpit technologies to increase the operational capacity of civilian rotary-wing crafts in degraded visual conditions. The current study provides preliminary validation for the usefulness of a future cockpit technology in improving pilot situation awareness and reducing workload during flight in degraded visual conditions. Such improvements were analogous to flight in clear visual conditions using traditional HDD, indicating the HUD and the additional information displayed reduced the pilots need to switch their flight mode from being proactive to reactive. The HUD design tested in the current study is not commercially available however, the current results offer encouragement for continued research concerning the usefulness and usability of HUDs in helicopter operations.

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*Table 1 –* Means and standard deviations of pilot’s subjective ratings of Heading, Rate of Descent, Groundspeed, Power Status, Landing, Drift, Workload and Inclination to Go-around across two conditions of weather and display type

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  | Mean ± SD | | | | F Value | | |
|  | **Clear** | | **Degraded** | |  |  | **Weather\* Display** |
|  | **No HUD** | **HUD** | **No HUD** | **HUD** | **Weather** | **Display** |
| Heading | 4.42 ± 1.43 | 6.17 ± 0.75 | 4.33 ± 0.82 | 5.83 ± 0.75 | 0.39 | 11.79\* | 0.86 |
| Descent | 4.50 ± 1.22 | 5.67 ± 1.03 | 4.00 ± 1.55 | 5.67 ± 1.03 | 0.25 | 22.23\*\* | 0.16 |
| Groundspeed | 4.17 ± 1.47 | 5.33 ± 1.37 | 2.67 ± 1.37 | 5.67 ± 1.03 | 1.00 | 30.94\*\* | 4.84 |
| Power Status | 4.33 ± 1.86 | 3.33 ± 1.97 | 3.33 ± 1.03 | 3.33 ± 1.51 | 1.15 | 0.87 | 0.56 |
| Landing | 6.33 ± 0.52 | 5.83 ± 0.98 | 4.33 ± 1.86 | 5.66 ± 1.51 | 1.83 | 1.63 | 20.86\*\* |
| Drift | 5.83 ± 0.75 | 5.17 ± 2.14 | 4.50 ± 1.87 | 5.67 ± 0.52 | 3.04 | 1.36 | 1.50 |
| Environment | 6.00 ± 0.63 | 6.17 ± 0.75 | 3.33 ± 1.97 | 5.00 ± 1.79 | 7.17\* | 5.79 | 3.31 |
| Bedford Scale |  |  |  |  |  |  |  |
| Workload | 3.00 ± 1.41 | 2.50 ± 0.84 | 6.17 ± 2.14 | 4.50 ± 2.07 | 7.74\* | 13.97\* | 1.57 |
| Confidence |  |  |  |  |  |  |  |
| Go-Around | 1.00 ± 0.00 | 1.00 ± 0.00 | 3.67 ± 2.50 | 2.33 ± 1.03 | 8.28\* | 3.48 | 3.48 |

\* *p* < 0.05, \*\* *p* < 0.01, \*\*\* *p* < 0.001

*Table 2* - Means and standard deviations of pilot’s time taken to reach and fly between flight gates

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  | Mean ± SD | | | | F Value | | |
|  | **Clear** | | **Degraded** | |  |  | **Weather\* Display** |
| Time | **No HUD** | **HUD** | **No HUD** | **HUD** | **Weather** | **Display** |
| Accumulated |  |  |  |  |  |  |  |
| Main effect | - | - | - | - | .89 | 1.61 | 103.05 |
| Total | 427.17 ± 113.30 | 353.17 ± 166.14 | 592.86 ± 144.16 | 526.83 ± 207.10 | 7.52\* | 2.93 | 0.01 |
| To 800 Feet | 170.16 ± 103.66 | 210.84 ± 71.87 | 308.92 ± 49.21 | 227.00 ± 143.21 | 6.50\* | .35 | 4.06 |
| To 600 Feet | 249.50 ± 94.09 | 193.17 ± 115.09 | 361.34 ± 67.52 | 251.83 ± 144.27 | 9.57\* | 8.10\* | .30 |
| To 400 Feet | 286.33 ± 96.28 | 211.17 ± 113.60 | 390.95 ± 39.92 | 294.50 ± 166.26 | 7.28\* | 8.95\* | .03 |
| To 200 Feet | 336.33 ± 91.20 | 285.00 ± 133.90 | 444.91 ± 58.24 | 406.33 ± 133.35 | 6.75\* | 6.39\* | .01 |
| To 100 Feet | 361.67 ± 96.75 | 304.67 ± 142.63 | 525.26 ± 99.25 | 440.58 ± 159.18 | 8.26\* | 11.38\* | .04 |
| To 50 Feet | 375.67 ± 97.27 | 321.83 ± 150.94 | 551.52 ± 115.09 | 465.33 ± 168.03 | 8.56\* | 7.34\* | .05 |
| Difference |  |  |  |  |  |  |  |
| 800 to 600 Feet | 79.33 ± 123.84 | 23.37 ± 9.70 | 56.43 ± 37.43 | 24.83 ± 19.36 | .24 | 2.34 | .26 |
| 600 to 400 Feet | 36.83 ± 19.44 | 18.00 ± 4.24 | 28.83 ± 43.25 | 42.67 ± 41.43 | .66 | .06 | 1.72 |
| 400 to 200 Feet | 50.00 ± 48.90 | 73.83 ± 134.97 | 50.70 ± 46.78 | 111.83 ± 116.01 | .20 | 4.45 | .43 |
| 200 to 100 Feet | 25.33 ± 11.18 | 19.67 ± 12.04 | 78.51 ± 50.26 | 34.25 ± 34.13 | 8.90\* | 4.76 | 2.54 |
| 100 to 50 Feet | 14.00 ± 5.37 | 17.17 ± 11.75 | 25.44 ± 17.60 | 24.75 ± 16.83 | 3.90 | .05 | .18 |
| 50 to Ground | 51.50 ± 32.62 | 31.33 ± 24.26 | 38.70 ± 34.77 | 61.50 ± 43.70 | .83 | .01 | 1.91 |

\* *p* < 0.05, \*\* *p* < 0.01, \*\*\* *p* < 0.001

*Figure 1 -* Landing symbology in HUD



*Figure 2* – Averaged flight profiles of pilots plotting altitude, longitude and latitude in clear and degraded visual conditions with and without HUD



*Figure 3* – Averaged flight profiles of pilots ploting altitude across time in clear and degraded visual conditions with and without HUD

