Use of Highways in the Sky and a Virtual Pad for Landing Head Up Display Symbology to enable improved Helicopter Pilots Situation Awareness and Workload in Degraded Visual Conditions

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**Abstract**

Flight within degraded visual conditions is a great challenge to pilots of rotary-wing craft. Environmental cues typically used to guide interpretation of speed, location and approach can become obscured, forcing the pilots to rely on data available from in-cockpit instrumentation. To ease the task of flight during degraded visual conditions, pilots require easy access to flight critical information. The current study examined the effect of “Highways in the Sky” symbology and a conformal virtual pad for landing presented using a Head Up Display (HUD) on pilots’ workload and situation awareness for both clear and degraded conditions across a series of simulated rotary-wing approach and landings. Results suggest that access to the HUD lead to significant improvements to pilots’ situation awareness, especially within degraded visual conditions. Importantly access to the HUD facilitated pilot awareness in all conditions. Results are discussed in terms of future HUD development.

**Key words:** Rotary-wing, Head-Up Display, Situation Awareness, Workload, Highways in the Sky

**Practitioner Summary**

This paper explores the use of a novel Heads Up Display, to facilitate rotary-wing pilots’ situation awareness and workload for simulated flights in both clear and degraded visual conditions. Results suggest that access to HUD facilitated pilots’ situation awareness, especially when flying in degraded conditions.

**Introduction**

Alongside technical malfunction, operating in degraded visual conditions is a leading cause of rotary-wing accidents (Baker, Shanahan, Haaland, Brady & Li, 2011). In addition, degraded visual conditions are a leading cause of disruption and delays in civil aviation (Pejovic, Noland, Williams & Toumi, 2009). Rotary-wing operations are greatly constrained by weather, especially for flight into instrument conditions, whereby flights start in clear conditions and subsequently degrade (Hart, 1988). Degraded visual conditions typically include issues relating to fog and rain, reducing visibility. Degraded visual conditions also occur when helicopters operating in arid environments, such as deserts, experience what is referred to as “Brownout”(Phillips & Brown, 2009). Within brownout scenarios, the helicopter rotors can disturb significant quantities of ground based particulate matter; forming dense particulate clouds, significantly reducing visibility and disrupting operations (Phillips, Brown, & Kim, 2011). Similar effects can occur within tundra terrain, whereby dense clouds of snow can form disrupting visibility in a “Whiteout” scenario (Newman, McMahon, & Avtn, 2012). Degraded visibility is therefore a key factor impacting rotary-wing operations globally and not limited to a single theatre of operations. With rotary-wing aircraft unable to safely complete critical phases of flight such as approach and landing in degraded visual conditions (Stanton, Plant, Roberts, Harvey, & Thomas, 2016), rotary-wing aircrafts key strength in their flexibility of operations, including flights to remote locations without aviation related ground infrastructure, can become their key limiting feature (Nascimento, Majumdar & Ochieng, 2014).

Despite the operational limitations of rotary-wing craft, demand for their use, both within military and civilian operations, is ever increasing, with such craft potentially forming a cornerstone in the integrated transport systems of the future (Stanton et al., 2016). Future technology could play a key role in overcoming the limitations of current rotary-wing operational windows (Andre, Wickens, Moorman & Boschelli, 1991). One technology that has seen considerable development is the use of synthetic vision systems (Prinzel III, et al., 2004). Synthetic vision systems can enable flights in degraded visual conditions without the pilot needing a direct view of their external environment (Foyle Kaiser & Johnson, 1992). One way of presenting synthetic vision information to pilots is via the use of a Head Up Display (HUD). A HUD, as used with rotary-wing setting, is a glass mounted panel in the pilots forward visual field displaying flight information, most commonly 2D traditional flight references (e.g. airspeed) and may potentially present a 3D (conformal) graphical representation of the external environment (Swail & Jennings, 1999; Thomas & Wickens, 2004; Prinzel III et al., 2004). HUDs can allow a pilot to fly eyes-out without the need to transfer their gaze to instruments in the cockpit (Stanton et al., 2016), enhancing their understanding of the current environment and subsequent levels of situation awareness as well as optimising workload (Snow & Reising, 1999; Fadden et al., 1998; Snow and French, 2002).

Cognitive workload 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). When flying in degraded visual conditions, pilots cannot rely on visual information from the external environment (Doehler et al., 2009). Consequently they are reliant upon cockpit instrumentation to guide their knowledge of the external environment, increasing cognitive workload (Snow & French, 2002; Harris, 2011; Klein, 1997; Wickens, 2002; Prinzel III, et al., 2004). There is consensus among researchers (Harris, 2011; Melzer, 2012) that future cockpit technology should optimise workload, particularly in degraded visual conditions in order to void overloading the pilot, which could potentially compromise safety. The current work aimed to develop a cockpit technology that reduces cognitive load, whilst simultaneously facilitates pilot situation awareness of external cues and technical flight parameters.

Although the concept and value of situation awareness is a hotly contested topic (Dekker & Hollnagel, 2004; Stanton, Salmon & Walker, 2015; Stanton, Salmon, Walker, Salas & Hancock, 2017), this debate is outside the scope of the current work, which focuses on pilots perceived situation awareness during a task. Despite disagreements over the nature of situation awareness, a considerable body of empirical evidence has been collected identifying its relevance, operational and scientific merit, especially within the domain of aviation (Parasuraman, Sheridan, & Wickens, 2008). One widely accepted definition for situation awareness is provided by Endsley, (2006) who argues that situation awareness is *“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” (p. 529).* Situation awareness is seen as key in modern flight operation, primarily as a consequence of the complexity of such tasks (Endsley & Jones, 2012). Pilots must work within technologically constrained environments, whilst integrating understanding of the larger environment and managing automation and workload (Endsley & Jones, 2012). This conceptualisation of situation awareness however considers that situation awareness lies solely with the human operator, in the case of aviation and rotary-wing operations specifically, the pilot. An alternative approach to situation awareness as a theoretical construct is provided by Stanton et al. (2006), whereby rather than being held solely in the mind of an operator, situation awareness is a property of the socio-technical system as a whole. Taken within this approach, situation awareness can be defined as *“activated knowledge for a specific task within a system....[and] the use of appropriate knowledge (held by individuals, captured by devices, etc.) which relates to the state of the environment and the changes as the situation develops.”* (Stanton et al. 2006, *p.* 1291). Although the socio-technical system approach to situation awareness remains controversial and can be seen as a radical departure away from its individualistic origins (Endsley, 2015), it has been argued that this approach can better account for the complex work of modern systems, especially when considering the complex work of automated systems (Stanton et al., 2017), including aviation (Harris & Stanton, 2010). Within rotary-wing operations, rather than the pilot having sole situation awareness, the pilot, flight instruments, sensors and display all possess knowledge of the overall system state and situation awareness is an overall property of the system, not individual components (Plant & Stanton, 2013; 2015; 2016). Facilitating synthetic vision technologies within flight operations, such as within a HUD can improve the situation awareness of the system as a whole, therefore leading to safer operations and potentially increasing the operational capabilities of the aircraft.

Within rotary-wing operations specifically, access to a HUD has been noted to positively inform the situation awareness and reducing the chance of error (Barrows & Powell, 1999). Typical flight controls can make it easy for a pilot to lose situation awareness and lose track of currently used reference points when completing complex manoeuvres such as 180° turns (Barrows & Powell, 1999). Within such manoeuvres, pilots are required to rapidly switch between use of cues within the external environment and use of instruments within the cockpit such as Head Down Displays (HDDs) as well as operate flight controls. Access to a HUD can act to greatly assist pilots by facilitating flight during instrument conditions (Stanton et al., 2016) and during complex manoeuvres (Barrows & Powell, 1999). The way information is displayed on the HUD is however critical for effective performance. If the HUD conveys too much information to pilots, or the layout and arrangement of the items is suboptimal, key elements within the outside environment can be neglected, and flying disrupted (Yeh, Merlo, Wickens & Brandenburg, 2003; Harris, 2011).

One design element within HUD displays is the use of constraining markers that pilots must fly through, or between, to reach a set goal. Although a variety of names for such display markers have popularised the literature, including “Tunnels in the Sky” (Regal & Whittington, 1995), “pathways” (Crawford & Neal, 2006) and “Highways in the Sky” (HITS, Williams, 2002), they all share a commonality in that the markers display a prediction of where, spatially, the aircraft should seek to be in the future. For consistency, the term Highway in the Sky or “HITS” is adopted within this paper. Although historically, HITS information has been presented as part of a HDD, access to HITS information transforms the task of flying from an integrative challenge, whereby pilots must synthesise data from multiple sources, both internal and external to the aircraft, into a boundary control task (Mulder, 2003). This information can help to simplify the flying task and has been documented to increase pilots’ situation awareness (Dorighi, Ellis, & Grunwald 1991; Regal & Whittington, 1995) whilst not increasing workload (Below, von Viebahn, & Hammer, 1995; Dorighi et al., 1991). Fadden, Ververs and Wickens (2001) conducted an investigation of the use of HITS, which they refer to as a pathway, in fixed-wing aircraft, exploring both the impact of providing this information as well as the differences in providing this information through HUDs or HDDs. Fadden et al., found that the combination of a HITS displayed on a HUD was most effective at reducing deviation from target locations. They argued that as the HUD imposed imagery over the real visual scene, less scanning behaviour was required between the real world and the information display, and consequently less disparity was observed between the external visual scene and information provided by the aircraft, allowing for greater synthesis of information (Levy, Foyle & McCann, 1998).

Due to the unique flight profiles of rotary-wing craft, especially during landing, which are dominated by short approach distances and relatively steep descent (Dodge & Brook, 2013), pilots can require additional visual cues for the critical landing phase. This can be achieved via the use of conformal symbology. Conformal, or scene-linked is often included on HUDs to increase the realism of the presented information (Snow & French, 2002). The use of conformal symbology allows information to be displayed at a static position relative to the real world, as such it is possible to impose an outline of a helipad displayed on the HUD which remains overlaid on top of the view of the outside world, regardless of what part of the HUD the pilot is looking at. This can be of critical importance to rotary-wing operations which includes flight to locations which do not include ground based infrastructure elements (Nascimento, Majumdar & Ochieng, 2014), as artificial landing zones can be digitally imposed upon terrain. The use of such conformal symbology leads to faster detection of changes in symbology and improved flight path tracking accuracy (Fadden et al., 1998; Snow and French, 2002), making it idea for use with the landing phase, whereby pilots must remain vigilant of the altitude and relative to visual cues.

As has been presented, operating and landing a rotary-wing aircraft is a great challenge, one that is further exacerbated when operating in poor visibility (Baker et al., 2011; Stanton et al., 2016). Although previous research has indicated that providing both HUD-based information and HITS information can enhance flight in fixed-wing craft, significantly less evidence is available for rotary-craft. The current study explores how access to a HUD, displaying HITS information, influences rotary-wing pilots’ situation awareness and workload, when operating within both simulated clear visual environments and simulated degraded visual environments.

Based on the results obtained using the initial HUD design (Stanton et al., 2016) and other prior research within the field (Fadden, Ververs & Wickens, 2001; Snow & French, 2002), it is hypothesized that:

1. Flight in degraded visual conditions without access to the HUD, displaying HITS markers and conformal symbology, will increase pilots’ workload and decrease situation awareness.
2. No difference in workload or situation awareness will be observed between flight in degraded visual conditions with the HUD, displaying HITS markers and conformal symbology, and clear visual conditions without HUD, displaying HITS markers and conformal symbology.
3. No difference in workload or situation awareness will occur with and without HUD, displaying HITS markers and conformal symbology, during flights within clear visual conditions.

**Method**

**Participants**

Participants were 13 male qualified rotary-wing pilots, aged 22 – 66 years *(M* = 46.15, *S.D* = 15.25, *Med* = 51*)*. Current estimates suggest that the population average of rotary-wing pilots is 43 years (Air Pilots, Flight Engineers and Flying Instructors, 2017). Participants had varying rotary-wing flight hours flown (30 – 9500 hours, *M* = 3336, *S.D.* = 3014, *Med* = 3000). Although no female participants were included within this study, recent evidence (McCarthy, Budd, & Ison, 2015) has identified that only 3% of pilots currently employed are female. Due to the overwhelming dominance of currently active male pilots and the small sample of participants employed within the study, the lack of female participants was not considered a significant weakness.

Participants were recruited via opportunity sampling, with posters disseminated at local airfields and via word of mouth. As part of the requirements of the study, all participants had flown a rotary-wing aircraft within a year of the study. Ethical approval for this study was granted by the Research Ethics Committee, University of Southampton (ID: 4032) and all participants provided informed written consent.

***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 (with or without HUD). The order conditions were presented to the participants was counterbalanced to minimise potential order effects. The dependant variables were pilots’ situation awareness as measured by the post-landing assessment questionnaire, including a measurement of pilots’ confidence and willingness to perform a go-around manoeuvre; pilots’ subjective workload as measured by the Bedford scale and pilots’ subjective workload as measured by NASA-TLX.

***Equipment and Materials***

*Flight simulator –* The study was conducted using a portable desktop-based flight simulator. The setup for the desktop-based simulator is presented in Figure 1. This portable set-up was chosen to increase the number of participants available to the study by allowing the simulator to be set in airfield based crew rooms. Previous research testing the HUD typically had access to low sample sizes, for example Stanton et al., (2016) who explored an earlier version of the HUD had a sample of only 6 participants when using a simulator based at the University of Southampton. The portable desktop flight simulator consisted of a laptop computer that displayed the head down display (HDD), three monitors mounted on a stand to raise the height above the laptop and flight controls. The three monitors displayed the simulated flight environment and the HUD. The simulated environment ran using Prepar3D (previously Microsoft flight simulator software). 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., 2016). The Prepar3D software is highly customisable and allowed the required weather conditions to be simulated. In the clear sky conditions, the clear weather setting was selected, allowing pilots a considerable view. In the degraded visibility conditions however application of the fog setting reduced visibility to approximately 0.5km. 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 connected to the flight simulator via a USB connection.

INSERT FIGURE 1

*Head down Display -* The Head down display (HDD) used as part of this study was available within the native 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. The HDD was available to the pilots in all four conditions. This was displayed to the pilots on the outer right multi-function display unit in the simulator.

*Head up Display -* The HUD used for this study was a bespoke design that was generated through a larger research project using Cognitive Work Analysis (Rasmussen, 1986; Vincente, 1999) and subject matter expert feedback (SME) (see Stanton & Plant, 2010; 2011; Stanton, et al., 2016). The primary object of the HUD was to assist pilots with performing approach and landing in a degraded visual environment. As it has been proposed that future HUDs will have access to full colour symbology (Fares, & Jordan, 2015), the HUD was designed as a full-colour system with an extended field-of-view in order to support future windshield displays (Crawford & Neal, 2006). To assist with the landing task, the HUD included numerous key sources of landing critical information including, HITS markers, drift indicators, a landing zone indicator, 3-D depth pyramid markers and a flight path indicator (Figure 2). The HITS flight path markers consisted of blue circles representing the flight path to fly to approach over the helipad. Each circle was positioned 0.5nm from each other and provided a visible flight path to the pilot (Figure 3). The blue circle HITS markers were informed by SMEs from a leading aircraft manufacturer, and were designed to be salient to be easily visible to the pilots, but not distracting from the overall flight task. The HITS markers used are not currently available within a commercial product. Two drift indicators were present within the HUD. The first drift indicator was associated with the ground speed indicator (Figure 4) and consisted of a dial indication of the lateral XY directional vector (with respect to the aircrafts heading). This dial rotates to the vectors angle and changes colour to provide an indication of drift: green represents forward movement (-45 to 45 degrees), amber represents sideways movement (either -45 to -135 degrees or 45 - 135 degrees) and red represents backwards movement (-135 to 135 degrees). The second drift indicator appeared at low speeds (below 30 knots) to assist with drift during the final hover phase when landing. This indicator was a crosshair attached to a vector line. An upward pointing vector line represents forward movement, downwards represents backwards movement and pointing to either side represents left or right drift respectively. The crosshair symbol could be used to assist the hover phase by aligning the centre of the crosshair with the ‘W’ of the gull wing on the attitude indicator (Figure 5). For the development of the landing zone indicator, rotary-wing crafts potential to land at unimproved landing sites without aviation-related ground infrastructure was considered. The landing zone indicator 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 in order to safely align the flight path vector. To further assist landing, 3-D augmented reality ‘pyramids’ around the front of the helipad provide visual references for the pilot, providing a sense of speed, direction and altitude. The smaller pyramids were 75ft high and the larger ones behind were 150ft high, providing the pilot with additional visual cues. When the shorter pyramids directly aligned with the larger ones, the pilot is directly over the centre of the landing site. The final addition to the HUD was a flight path vector, which also acted as a touch down indicator. The flight path vector became visible to the pilot when losing altitude, and represents the point on the ground the helicopter will land if the current velocity is maintained (number 5, figure 2).

INSERT FIGURE 2

INSERT FIGURE 3

INSERT FIGURE 4

INSERT FIGURE 5

*Questionnaires* - Three questionnaires were administered to participants in order to collect subjective ratings of situation awareness and workload. The questionnaires were administered immediately following each simulated flight. The three questionnaires were a post-landing assessment, the Bedford Workload scale and the NASA-TLX.

The post-landing assessment questionnaire was developed by SMEs at a leading rotary-wing aircraft manufacturer, and has been previously utilised in Stanton, et al., (2016). The questionnaire required participants to rate their awareness of various flight parameters (e.g. desired heading, desired rate of descent) from 1 (low) to 7 (high). This questionnaire therefore offered a measure of perceived subjective situation awareness. In addition to assessing situation awareness, the post-landing assessment questionnaire also asked for a rating of pilots’ confidence, as measured by 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 unidimensional 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.

Participants also completed the NASA-TLX, a multidimensional tool designed to measure participants’ subjective perceived workload (Hart & Staveland, 1988). The NASA-TLX is comprised of six measures of workload, Mental, Physical, Temporal Demand, Performance, Effort and Frustration, which can be combined into an overall workload score (Hart, 2006).

***Procedure***

Prior to the start of the investigation, participants were briefed about the study and presented with a consent form and demographic questionnaire. Participants completed an initial familiarisation session with the simulator to ensure that data gathered as part of the empirical trials was not influenced by a lack of knowledge of basic controls. Participants were also familiarised with the HUD in a talk through provided by the software developer to explain each instrument and the displayed symbology. Participants also practiced flying with the HUD prior to the start of the study. The familiarisation session lasted approximately 25 minutes. Following familiarisation, the participants independently flew each of the four experimental conditions (clear, clear + HUD, degraded and degraded + HUD). In each condition participants started 1nm out to sea, at a height of 1500 feet and at a speed of 35 knots. Participants were instructed to fly to the runway and land the aircraft. The runway was visible from the start in the clear sky conditions, however for conditions within the degraded visual environment, pilots were provided with a heading and precision approach path indicators but no other tools (e.g. radio navigation). Following each condition, the post-landing assessment questionnaire, the Bedford workload questionnaire and the NASA-TLX 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. Once pilots had completed all four conditions, a member of the research team debriefed them.

**Data Reduction and Statistical Analysis**

The sample size of the current study was relatively small, however, as the design was within-subjects, it was decided to proceed with statistical assessment. When choosing factors to include in each statistical model, family wise error rates were considered and collinearity examined. It was decided to examine all sub-factors of awareness and NASA-TLX in separate models, with appropriate post-hoc analysis conducted. Bedford workload measurements and confidence were examined in separate models.

Firstly, 2 x 2 within-subjects multivariate analyses of variance (MANOVAs) examined how display type and weather conditions impact upon pilot’s subjective situation awareness ratings, 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. ANOVAs were conducted rather than *t*-tests for purposes of consistency and to account for family wise error rates. The parametric tests used here are robust to violations of normality and homogeneity of variance (Fowler, 1987; Glass & Stanley, 1970; Howell, 1992; Keselman, Algina & Kowlchuk, 2002; Kirk, 1968). To account for multiple comparisons, the Bonferroni correction method was used for all parametric analysis.

**RESULTS**

As noted within the methods, three main variables were considered as part of the analysis, participants’ perceived levels of situation awareness, confidence, as represented by their likeliness to perform a go-around and participants’ workload as measured by the post trial questionnaires. Data and results are presented within table 1.

INSERT TABLE 1.

**Post-landing Questionnaire**

A significant main effect of weather (*F*1, 12 = 8.07, *p* < .05, ήp2 = .90) was observed on pilots’ awareness, suggesting that the visual condition influenced participants’ level of awareness. No main effect of symbology (*F*1, 12 = 2.91, *p* = .09, *ns*), and no significant interaction between weather and symbology was observed (*F*1, 12 = 1.69, *ns*). Despite limited main effects, due to 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.

Pilots’ awareness of rate of descent (*F*1, 12 =5.85, *p* < .05, ήp2 = .33) and outside environment (*F*1, 12 =18.88, *p* < .01, ήp2 = .61) was significantly affected by weather. Post hoc analyses revealed pilot awareness of rate of descent and the outside environment is significantly higher (*p* < .05) in clear visual conditions with no HUD than degraded visual conditions with no HUD (see table 1). Pilots’ awareness of the outside environment was significantly higher (*p* < .05) in clear visual conditions with HUD than degraded visual conditions with HUD (see table 1). Non-significant trends were observed for the effect of weather on awareness of required landing (*F*1, 12 =4.04, *p* = .07, *ns*) and drift (*F*1, 17 = 4.39, *p* = .06, *ns)*. Post hoc analyses revealed pilot awareness of both landing and drift was significantly higher (*p* < .05) in clear visual conditions with no HUD than degraded visual conditions with HUD. Pilots’ level of awareness of landing point and drift was also higher in clear visual conditions with HUD than in the degraded visual conditions with HUD, although such differences were not significant (*p* > .05). Weather did not significantly impact upon pilot awareness of desired heading (*F*1, 12 = 2.55, *ns*), groundspeed (*F*1, 12 = 2.08, *ns*) or power status (*F*1, 12 = 1.92, *ns*).

Pilot awareness of desired heading (*F*1, 12 = 7.56, *p* < .05, ήp2 = .39), rate of descent (*F*1, 12 = 10.36, *p* < .01, ήp2 = .46), groundspeed (*F*1, 12 = 11.11, *p* < .01, ήp2 = .48), power status (*F*1, 12 = 8.91, *p* < .05, ήp2 = .43) and drift (*F*1, 12 = 23.33, *p* < .01, ήp2 = .66) were significantly affected by symbology. Post hoc analyses revealed that pilot awareness of rate of descent, groundspeed, power status and drift was significantly (*p* < .05) higher when they had access to the HUD than when they did not have access to the HUD, in both clear and degraded visual conditions (see table 1). Pilots’ awareness of heading was significantly higher when they had access to the HUD than when they did not have access to the HUD when flying in degraded visual conditions (see table 1). A similar trend for higher awareness of heading was also apparent when pilots had access to the HUD in clear conditions (see table 1), although such differences were not significant (*p* > .05). In contrast, pilots’ awareness of required landing point (*F* < 1, *ns*) and outside environment (*F* < 1, *ns*) were not significantly affected by the symbology.

Pilot awareness of rate of descent (*F <* 1, *ns*), groundspeed (*F* < 1, *ns*), power status (*F* < 1*, ns*), required landing point (*F* < 1*, ns*) and outside environment (*F* < 1, *ns*) were not significantly affected by interactions between weather and display. Non-significant trends for the effect of the interaction between weather and display were however observed for pilots’ awareness of desired heading (*F*1, 12 = 3.86, *p* = .07, *ns*) and drift (*F*1, 12 = 4.35, *p* = .06, *ns*). Post hoc analyses revealed pilot awareness of heading and drift was significantly (*p* < .05) lower in degraded visual conditions with no HUD than in clear visual conditions with HUD. Pilot awareness of drift was significantly (*p* < .05) in degraded visual conditions with HUD than clear visual conditions without HUD. Pilot awareness of heading was higher in degraded visual conditions with HUD than clear visual conditions without HUD, although such differences were not significant (*p* > .05).

**Confidence/ Go-Around**

Pilots’ likeliness to performance go-around was significantly affected by weather (*F*1, 12 = 13.81, *p* < .01, ήp2 = .54). Post hoc analyses revealed pilots likeliness to go around was significantly higher (*p* < .05) in degraded visual conditions with no HUD, than clear visual conditions with no HUD (see table 1). Pilot likeliness to go around was also significantly higher (p <.05) in degraded visual conditions with HUD than clear visual conditions with HUD (see table 1). No significant effect of symbology on pilot likeliness to go around (*F*< 1, *ns*) or interaction between weather and symbology (*F* < 1, *ns*) was observed.

**Workload – Bedford Scale**

Figure 6 presents pilots perceived workload, as measured by the Bedford scale. From this figure, it is clear that the flight and landing task within the degraded visual environment without the HUD was associated with the greatest level of workload. Conversely, flight within clear conditions with access to the HUD was associated with the lowest recorded workload, suggesting that the HUD acted to reduce workload even in clear conditions.

INSERT FIGURE 6.

Examining the results from Bedford scale via the use of a univariate ANOVA, it was found that workload was significantly affected by weather (*F*1, 12 = 9.56, *p* < .01, ήp2 = .44). Post hoc analyses revealed that pilots’ workload was significantly higher (*p* < .05) in degraded visual conditions with no HUD than during clear visual conditions with no HUD (see table 1). Pilots’ workload was also higher in degraded visual conditions with HUD than clear visual conditions with HUD (see Table 1 and Figure 6), although such differences were not significant (*p* >.05). No significant effect of symbology (*F*1, 12 = 2.45, *ns*) or interaction between symbology and weather (*F*1, 12 = 4.02, *ns*) were observed on pilot workload. These findings suggest that access to the HUD facilitated pilot workload, however a grater sample size would be required in order to observe statistical significance.

**Workload - NASA-TLX**

When examining results from the NASA-TLX, a significant main effect of weather was observed (*F*1, 12 = 4.48, *p* < .05, ήp2 = .79), workload differed between flights in clear and degraded visual conditions. No significant main effect of symbology (*F* < 1, *ns*) or significant interaction effect between weather and display (*F*1, 12 = 2.53, *ns*) were observed however, suggesting that access to a HUD did not impact NASA-TLX workload. Despite the limited main effects, due to 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.

Pilots’ mental workload was significantly affected by weather (*F*1, 12 = 9.19, *p* < .01, ήp2 = .43). Post hoc analyses revealed pilots’ mental workload was significantly higher (*p* < .05) in degraded visual conditions with no HUD than in clear visual conditions with no HUD (see table 1). The finding suggests that operating within degraded visual environments increased pilots’ mental workload. In contrast, although pilots’ mental workload was higher in degraded visual conditions with HUD than clear visual conditions with HUD (see table 1), such differences were not significant (*p* >.05). This suggests that the HUD acted to reduce the increase in workload associated with operating in degraded visual conditions. A non-significant trend for the impact of symbology on temporal load (*F*1, 12 = 3.48, *p* = .08, *ns*) was observed. Post hoc analyses revealed pilot temporal load was higher without HUD than with HUD both in clear and degraded visual conditions, although partially as a consequence of the sample size employed within the current study, such differences were not significant (*p* > .05). No significant effect of symbology was observed on pilots’ physical workload (*F*1, 12 = 2.00, *ns*), metal workload (*F*1, 12 =1.77, *ns*), performance (*F*1, 12 = 1.70, *ns*), effort (*F*1, 12 = 2.96, *ns*), frustration (*F* > 1, *ns*) or overall workload (*F*1, 12 = 2.36, *ns*). No significant effect of weather was observed on pilots’ physical workload (*F*1, 12 = 1.85, *ns*), temporal workload (*F*1, 12 = 1.53, *ns*), performance (*F*1, 12 = 1.27, *ns*), effort (*F*1, 12 =2.36, *ns*), frustration (*F*1, 12 = 2.85, *ns*) or overall workload (*F*1, 12 = 1.44, *ns*).

No significant interaction effects between weather and display were observed on pilots’ mental workload (*F*1, 12 = 1.57, *ns*), physical workload (*F*1, 12 = 1.54, *ns*), temporal workload (*F* < 1, *ns*), performance (*F*1, 12 = 1.58, *ns*), effort (*F >* 1, *ns*), frustration (*F* > 1, *ns*) or overall workload (*F*1, 12 = 1.07, *ns*).

Overall results suggest that weather significantly impacted pilots’ perceived workload. Although access to the HUD did appear to reduce pilots’ workload when operating in degraded visual conditions, due to the limited sample size within the current study this rarely reached statistical significance. The HUD did not however appear to negatively impact pilots’ workload when flying in clear conditions.

**Discussion**

Results indicated that access to the HUD led to several significant improvements of pilot perceived situation awareness. This effect was most prominent when comparing the use of the HUD in degraded compared to clear visual conditions. Limited differences in pilots’ subjective workload or perceived situation awareness with or without the HUD were seen within the clear visual conditions, indicating that access to the HUD did not impede participant performance. Pilot awareness of rate of descent, groundspeed and drift was significantly higher in clear visual conditions with the HUD than in clear visual conditions without the HUD, with all other awareness exhibiting no significant change (but not decreasing). In general, pilot workload was lower when the HUD was present than when it was not, both in clear and degraded conditions, although such results were typically not significant due to the limited sample size. Results overall suggest that access to the HUD was beneficial, rather than a hindrance.

Flight in degraded visual conditions significantly reduced pilot’s awareness of rate of descent and outside environment, as would be anticipated from previous research (Phillips, Brown, & Kim, 2011; Stanton et al., 2016). In general pilot workload was significantly higher in degraded visual conditions that in clear visual conditions (Bedford scale), in particular mental workload (NASA-TLX). The likeliness of a go around being performed was also significantly higher in degraded visual conditions. These results offer validation for the experimental manipulation, in that visual conditions were degraded to a sufficient extent that a reliance on external information could not be maintained.

During flight within degraded visual conditions, the HUD significantly increased pilot’s awareness of desired heading, rate of descent, groundspeed, power status and drift compared to flight in degraded visual conditions with no HUD, although no difference was observed between awareness of the outside environment and landing site. The inclusion of HITS in the tested HUD was aimed at targeting awareness of such parameters, by providing a visual representation of the ideal flight path. Previous research has identified that HITS lead to increased maintenance of lateral and vertical flight path awareness (Williams et al., 2001). It does appear however that within the current study, the improvement of these flight profile awareness measures may have been at the cost of pilot’s awareness of the outside environment and landing site, a finding reminiscent of attentional tunnelling (Wickens & Alexander, 2009). Attentional tunnelling occurs when attention is allocated to a particular channel of information (e.g. HITS), for longer than is optimal, consequently resulting in the neglection of other relevant sources of information, such as the external environment or the neglection of key tasks (Wickens & Alexander, 2009; Snow & French 2002). Pilots did comment that the way in which the HITS was visually presented (circles to be flown through, figures 2 and 3) was problematic, and may have been partially responsible for the reduced awareness of the outside environment evoked by the HUD. Excluding the outside environment, pilots awareness of all other flight parameters were maintained during flight within degraded visual conditions to levels similar to flight in clear visual conditions without the HUD. This finding indicates that the presentation of a synthetic external environment allowed the pilots to continue to fly in an anticipatory as opposed to reactive fashion (Endsley, Farley, Jones, Midkiff, & Hansman, 1998). Previous research has indicated that the inclusion of synthetic terrain significantly improves situation awareness potential of HITS (Snow & Reising, 1999), a finding supported by the current study. In general, pilots’ workload when using the HUD in degraded visual conditions was not significantly different to when the HUD was available within flight in clear conditions. Workload was generally lower when pilots had access to the HUD, but results were typically not significant. This indicates that whilst certain awareness parameters were improved, this was at the cost of not reducing pilot workload. Despite this, levels of workload were not significantly higher when using the HUD in degraded visual conditions than with no HUD in clear visual conditions, indicating the cognitive costs of using the current HUD are not overly detrimental.

Results indicate that the workload of pilots was slightly reduced when using the HUD, particularly in degraded visual conditions, however this improvement was rarely significant. The fact that the reductions in workload were not significant suggests that the HUD did not simplify the task, however it was seen that the HUD did not increase workload, which can be seen as a positive outcome. Feedback from pilots revealed that they found the HITS and virtual pad for landing in the HUD beneficial, a finding supported by performance data, including significant improvements in awareness of heading and rate of descent when it was used. However, the visual display of the HITS was reported as problematic as pilots were required to fly through circles. Pilots verbally indicated that they felt extremely uncomfortable flying through anything, regardless of the nature of the markers as just virtual flight path indicators. It appears therefore that the facilitative effects of the HUD concept are being constrained by the cognitive cost of pilots being required to fly through virtual objects. The improvements observed were also at the cost of other awareness parameters, including the outside environment, suggesting the current HUD concept is inappropriately holding the attention of the pilots. Despite these limitations, the significant improvements to perceived situation awareness and non-significant reductions in workload are extremely encouraging given the pilots recorded dislike of the manner in which the HITS was presented. The feedback from pilots also indicated that the reason the HITS presentation had not been detrimental to performance was due to the fact the benefits of the HUD are most prominent during the final phase of landing, taking advantage of the virtual pad for landing rather than during the descent phase.

**Conclusion**

This study explored the impact of a novel HUD display, utilising HITS markers and a virtual pad for landing, on pilots perceived situation awareness and workload, for flight and landing in both clear and degraded visual conditions. Results indicated that the HUD facilitated pilots perceived situation awareness and reduced workload, especially during flight within degraded visual conditions. Although data rarely reached the level required for statistical significance, it was seen that the HUD was of benefit in all flight conditions. Pilots did comment that the graphical representations negatively influenced their actions however, suggesting that fully enclosed markers are not desirable. Future iterations of design should seek to utilise HUD based HITS markers, to facilitate performance, as demonstrated within the current work, but to do so in a way which is accommodating of pilots desires, encouraging greater use and adoption of the technology.

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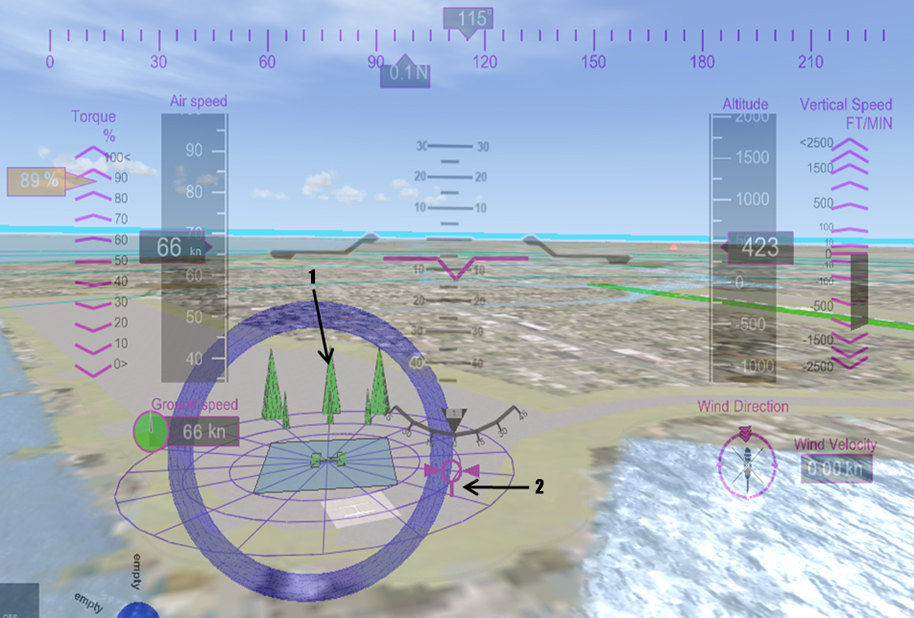
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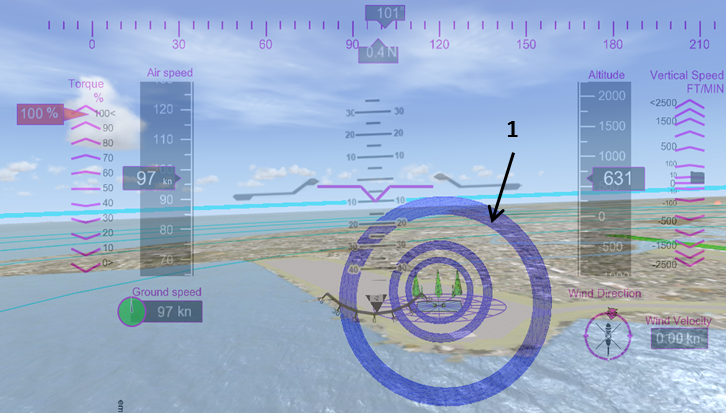
Figures & Figure Captions



*Figure 1 –* Mobile Simulator layout.



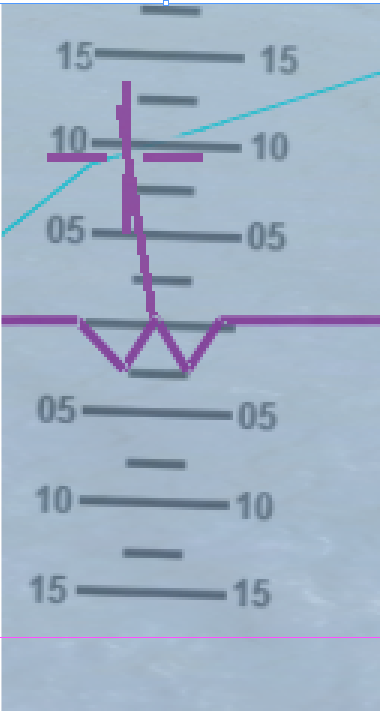
*Figure 2* – HITS indicator and potential landing zone marker. 1 indicates 3D depth pyramid markers, and 2 is a Crosshair Drift Indicator.



*Figure 3-* MultipleHITS markers visible on approach to the landing zone.



*Figure 4* - Ground speed and drift indicator



*Figure 5 -* Drift indicator showing forward movement

*Figure 6 –* Mean Bedford Workload Rating

Tables

Table 1 – Means and standard deviations of pilot’s subjective ratings across two conditions of weather and display type

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Mean ± SD | | | | | F Value | | | | |
|  | **Clear** | | **Fog** | | |  |  | | | **Weat\* HUD** |
|  | **No HUD** | **HUD** | **No HUD** | **HUD** | | **HUD** | **Weather** | | |
| Post Landing Assessment | | | | | | | | |  | |
| Main Effect | - | - | - | - | 2.91t | | | 8.07\*\* | 1.69 | |
| Head | 4.69 ± 1.49 | 5.46 ± 1.71 | 3.62 ± 1.94 | 5.46 ± 1.51 | 7.56\* | | | 2.55 | 3.86t | |
| Descent | 4.23 ± 1.42 | 5.46 ± 1.66 | 3.69 ± 1.75 | 4.92 ± 1.75 | 10.36\*\* | | | 5.85\* | 0.00 | |
| GS | 3.15 ± 1.57 | 4.77 ± 1.24 | 3.00 ± 1.47 | 4.54 ± 1.56 | 11.11\*\* | | | 2.08 | 0.03 | |
| PS | 4.31 ± 1.65 | 5.23 ± 1.48 | 3.85 ± 1.68 | 4.92 ± 1.55 | 8.91\* | | | 2.69 | 0.10 | |
| Landing | 6.23 ± 0.83 | 6.08 ± 1.55 | 4.92 ± 1.93 | 5.54 ± 1.56 | 0.25 | | | 4.04t | 0.92 | |
| Drift | 3.62 ± 1.45 | 5.15 ± 1.46 | 2.54 ± 1.51 | 4.92 ± 1.32 | 23.33\*\*\* | | | 4.39t | 4.35t | |
| ENV | 5.23 ± 1.59 | 5.23 ± 1.36 | 4.00 ± 1.96 | 3.92 ± 1.71 | 0.01 | | | 18.88\*\*\* | 0.02 | |
| Confidence |  |  |  |  |  | | |  |  | |
| Go-Around | 2.77 ± 1.79 | 2.15 ± 1.72 | 4.31 ± 2.43 | 3.69 ± 2.18 | 0.90 | | | 13.81\*\* | .00 | |
| Bedford Workload | |  |  |  |  | | |  |  | |
| WL | 4.23 ± 2.01 | 3.76 ± 1.24 | 5.69 ± 2.14 | 4.46 ± 1.76 | 2.50 | | | 9.56\*\* | 1.91 | |
| NASA-TLX | | | | | | | | |  | |
| Main Effect | - | - | - | - | | .42 | 4.48\* | | 1.30 | |
| Mental | 10.38 ± 4.63 | 8.85 ± 4.74 | 13.69 ± 4.48 | 10.77 ± 4.73 | | 1.77 | 9.19\* | | 1.57 | |
| Physical | 9.31 ± 4.57 | 8.38 ± 5.08 | 11.54 ± 4.27 | 9.31 ± 4.44 | | 2.00 | 1.85 | | 1.54 | |
| Temporal | 9.54 ± 2.85 | 7.46 ± 3.28 | 10.31 ± 4.19 | 8.62 ± 3.18 | | 3.48t | 1.53 | | 0.06 | |
| Performance | 8.69 ± 4.33 | 11.85 ± 4.76 | 9.15 ± 6.19 | 9.23 ± 4.76 | | 1.70 | 1.27 | | 1.58 | |
| Effort | 12.77 ± 4.11 | 10.00 ± 4.40 | 13.46 ± 4.03 | 11.23 ± 4.32 | | 2.96 | 2.36 | | 0.21 | |
| Frustration | 10.23 ± 3.96 | 11.31 ± 4.82 | 8.15 ± 4.91 | 9.85 ± 4.98 | | 0.91 | 2.85 | | 0.12 | |
| Overall WL | 60.92 ± 12.58 | 57.85 ± 11.25 | 66.31 ± 14.29 | 59.00 ± 9.73 | | 2.36 | 1.43 | | 1.07 | |
|  |  |  |  |  | |  |  | |  | |

\* *p* < .05, \*\* *p* < .01, \*\*\* *p* < 0.001, t*p* < 0.15 (Non-significant Trend)