Envisioning Mixed Realities on the Flight Deck

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Abstract. Conformal 3D symbology presented on a head tracked head-mounted display (HMD) has the capability to enhanced pilot situation awareness, performance and workload by providing an unlimited field of view of operational hazards. In recent years, a body of research has emerged highlighting the technical advancements (i.e. HMD encumbrance and optical enhancements) that could enable the unique capabilities and benefits of HMDs to be realized on commercial and business flight decks in the near future. The current paper provides a systematic review of the HMD-related pilot benefits (performance, workload, situational awareness, and usability) that have been reported in the literature. We conclude by highlighting the operational contexts where HMDs might enhance pilot performance, flight safety and efficiencies.

Keywords: Head-Mounted displays · Conformal symbology · Pilot performance

1 Introduction

The potential of three-dimensional (3D) displays has attracted considerable interest from the aviation community as a means of further enhancing the intuitive nature in which information is presented to the pilot. Extensive research has documented the situational awareness (SA) benefits afforded by 3D displays. For example, compared to a two-dimensional (2D) orthogonal representations of flight information (e.g. altitude and geographical position on a navigation display (ND)), a 3D representation is able to depict an intuitively understandable spatio-temporal representation of the aircraft's current situation [1]. This is particularly the case for forward perspective 3D displays with the capability of generating virtual "conformal" symbology that can be accurately mapped to geographically locations within the forward perspective scene [2, 3]. Conformal symbology can be "truly conformal", where the imagery directly overlays real objects that exist within the outside scene (e.g. the horizon line or a runway overlay as seen on a head-up display (HUD)). Or the symbology can be "virtually conformal", where the imagery can represent an entity in space that has no real physical properties (e.g. the pilot's perspective flight-path [1]). The combination of the above symbology conformity types presented onto an outside scene, in a sense, generates a mixed-reality flying environment.

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A large body of evidence exists showing that conformal symbology, presented on a HUD or on a perspective, synthetic vision (SV) head down display, improves flight path tracking and the detection of changes in symbology or traffic (see Fadden, Ververs and Wickens [2] for a meta-analysis). A HUD is a glass-mounted panel fixed within the pilot's near visual field. It allows the pilot to remain "head-up and eyes-out" as near-domain 2D flight information can be overlaid against far-domain 3D information belonging to the external scene [4, 5]. A SV display, on the other hand, presents the pilot with a 3D graphical rendering of a synthetic out-the-window perspective view. In the cockpit, a SV display can be located at either head-up or head-down. Whilst both HUD and SV displays can present information simultaneously in 2D and 3D formats, the coupling of airspace hazard information is more difficult due to the relatively narrow field of view available with the forward perspective view inherent in these displays [6].

Head-mounted displays (HMD), that can be coupled with low latency head-trackers, provide a viable solution to the previously mentioned field of view limitation by granting an unlimited field of regard [7, 8]. Indeed, in the business domain Thales plans to introduce an upgraded variant of their TopMax HMD that has the capability to present both 2D traditional flight references (e.g. airspeed, altitude and power) and 3D conformal imagery. A recent review by Arthur et al. [9] summarized the past 30 years of National Aeronautics and Space Administration (NASA) research of optimizing the collimated optics, head tracking, latency, and weight of HMDs. In terms of operational capabilities, they highlight the potential benefits of a HMD as a key enabler of multiple future air traffic concepts, for example, supporting the safety of simultaneous parallel runways operations where off-boresight traffic monitoring will be important [10]. However, it was concluded that in order for HMDs to see wide adoption in current business and commercial operational contexts HMDs will need to demonstrate equivalence, in terms of both performance and safety, to HUDs.

In this paper, we review literature from the aviation literature from the past 20 years to highlight the performance, workload (WL), SA and usability benefits associated with HMDs. A number of reviews exist describing the perceptual and human factors issues associated with HUDs [2, 4] and 3Ds displays more broadly [11, 12]. In regards to HMDs specifically, in the past 5 years there have been several reviews published by NASA [9, 13] and the German Aerospace Centre (DLR) [8] that detail the findings from their respective research programs on the application of HMDs in commercial and business aircraft and rotorcraft. However, these reviews predominantly adopt a technical focus (i.e. describe HMD encumbrance and optical enhancements) with minimal human factors related discourse. Hence, the purpose of the current paper is to provide a review of the existing empirical HMD evidence with a greater focus on highlighting the associated human factors issues. Furthermore, we try to examine the potential of "HUD equivalence" by only reviewing papers that compare HMD symbology with other symbology types. Be that symbology on the head-down or, preferably, head-up location. The review is structured according to two phases of flight to describe the value of HMDs within different aviation contexts. These include 1) approach/landing and 2) taxiing/ground operations.

2 Methods

Inclusion criteria for experiments required that experiments report at least one measure of performance (e.g. path deviation), WL (e.g. subjective scales, physiology measure), SA, or usability. Experiments were required to contrast HMD symbology to other symbology types (e.g. HUD and/or head down display). Each experiment was classified into one of two different types depending upon the phase of flight the HMD was being implemented in: 1) approaching/landing and 2) taxiing/ground operations.

3 Results

Eight experiments from the aviation human factors literature were identified. Two experiments were described in a single study by Arthur et al. (2014) [14]. Outcomes of the eight experiments were classified as: 1), HMD outcomes were found to be better than alternative symbology formats (e.g. HUD or head down ILS), 2); outcomes between the symbology types was equivalent, or 3); a HMD was found to be inferior to an alternative symbology formats. A summary of the literature review results is presented in Table 1.

Table 1 Results of the literature review for comparing HMD symbology to alternative symbology formats on performance, workload (WL), situational awareness (SA) and usability on approach/landing and taxiing tasks. Asterisks (*) are used to mark findings that were statistically verified.

Author	Date	Craft	Compared	Sample (*N*)	HMD outcomes			
Approach/Landing					**Performance**	**WL**	**SA**	**Usability**
Lorenz, Helmut & Schmerwitz [15]	2005	Fixed Wing	HDD	18	HMD Better*	Equivalent*	HMD Worse*	Equivalent
Arthur et al. [14]	2014	Fixed Wing	HUD	12	Equivalent*	Equivalent*	Equivalent*	Equivalent
Doehler et al. [19]	2015	Rotary	HDD	6	HMD Better	-	-	HMD Better
Schmerwitz et al. [20]	2015	Rotary	HDD	18	HMD Better	Equivalent	-	HMD Better*
Doehler et al. [21]	2012	Rotary	HDD	12	Equivalent	Equivalent	Equivalent	HMD Better*
Taxi/Ground Ops								
Bailey et al. [22]	2007	Fixed Wing	HUD HDD	8	-	Equivalent*	Equivalent*	HMD Better
Arthur et al [23]	2009	Fixed Wing	HUD HDD	8	Equivalent*	Equivalent*	Equivalent*	-
Arthur et al. [14]	2014	Fixed Wing	HUD HDD	12	Equivalent*	Equivalent*	Equivalent*	Equivalent

3.1 Approach and Landing

The literature review identified five human-in-the-loop experiments examining the benefits of a HMD device during approach and landing. A single study, Arthur et al. [14], directly compared a HMD to a HUD, in a scenario that involved a straight approach, landing, and taxi with a fixed-winged commercial aircraft. The two HMD symbology variants included a version where the PFD symbology was fixed to the pilot's gaze direction and a version that was fixed to the HUD combiner glass location (creating an "artificial HUD"). Pilot performance, workload and situational awareness was equivalent across the three symbology types. One possibility for this outcome is that the complexity of a straight approach task did not lend itself to the larger field of regard benefits that are afforded by a HMD. This is supported by an earlier study by Lorenz et al. [15] where tracking performance during a curved approach was enhanced by presenting a perspective flight-path on a HMD, compared to a head-down display. The advantage of a HMD for following curved trajectories would be expected based on the work by Mulder [16]; The reduced field of regard provided by a fixed perspective display (i.e. HUD or head down SV) can make it more difficult to follow curved trajectories. Taking these results together, a more detailed understanding of HMD benefits could be achieved in future studies examining different HMD symbology variants (e.g. the "artificial HUD" from Arthur et al. [14]) in operational contexts that require greater off-boresight monitoring. Interestingly, in the same study by Lorenz, SA with the HMD was worse compared to following the ILS on the head-down display, whereby detection of an unexpected event (detecting a runway incursion on approach) occurred significantly later with the HMD. This is an example of attentional capture, which is a common findings of studies investigating HUD presented perspective flight-path displays [5, 17]. However, it should be noted that the sample used in the study consisted entirely of trainee pilots with no HUD experience, potentially making them more susceptible to attentional capture effects [5].

The remaining three studies all concern a comparison between a HMD and head down display. These studies are based upon DLR research efforts to develop a 3D conformal helicopter landing symbology set that can be presented either on a HMD or head-down display [18]. Two of the studies, Doehler et al. [19] and Schmerwitz et al. [20], demonstrated that pilot landing performance was enhanced by presenting conformal 3D symbology representing the target landing zone on a HMD. Specifically, lateral drift near to touchdown was reduced when using the HMD. This is an expected benefit of a HMD, as the landing pad remains viewable on a HMD display at all times, in contrast to the head-down alternative that requires switching of attention between the head-down ND and being eyes-out. These enhanced performance findings were complimented by pilots higher usability ratings of the HMDs. Unfortunately, neither study reported the statistical results for these performance findings. Whilst this is understandable with the smaller sample size of six pilots included in Doehler's experiment [19], there existed no reported statistical analysis of the performance results in the experiment by Schmerwitz [20]. In contrast, statistical results were reported for the workload and HMD usability findings in the same study. The remaining study by Doehler [21] presented a comparison between a binocular HMD, a monocular HMD and a head down primary flight display (PFD) during a low-visibility landing task.

While pilots reported significantly higher acceptance for the binocular HMD, there were no significant workload or SA differences between symbology types. Possibly due to the employed landing task not being demanding enough. It was noted, however, that the lack of any significant performance findings could have been attributed to the insufficient handling qualities of the study's simulator platform. Unfortunately, similar to the previous two studies, no statistical analysis was presented for the pilots landing performance findings.

3.2 Taxiing/Ground Operations

Three experiments were identified that compared the benefits of a HMD, a HUD and a head-down display during taxiing operations. One of these experiments was conducted alongside one of the experiments described above (Arthur et al. [22]). Similar to the comparison between a HMD, HUD and a head-down display during approach, no significant difference was found in performance (i.e. centerline tracking), WL, SA and usability whilst taxing. The remaining two studies revealed that a SV HMD could enhance safety and improve ground operation efficiencies in a future air traffic environment across a range of visibility conditions. In both studies, 3D conformal symbology was presented on either a SV HMD or HUD to depict taxi routing and traffic information. Pilots were better able to perform the taxi task and reported significantly higher SA with the SV HWD concept compared to a head-down moving map or paper charts. However, whilst there was a preference shown by pilots for the HMD, there were no observed performance benefits of the HMD over the HUD.

4 Discussion

The purpose of the current paper was to review the empirical evidence that HMDs could enhance the safety and efficiency of flight operations in future or current air traffic environments. In terms of performance, firstly, HMD related performance enhancements were consistently observed within flying scenarios where off-boresight monitoring was required. For example, scenarios that required tracking a landing zone or curved trajectory during an approach in a helicopter [19, 20] of fixed-wing aircraft [15], respectively. Secondly, HMD performance was equivalent to alternative symbology types during scenarios where the majority of task-related information was located within the boresight location (e.g. flying a straight approach [14] or following a taxi route [23]). Together, the HMD performance findings across studies are overall positive, particularly in the absence of any reported HMD related performance decrements. This could be attributed to the technical advancements seen in HMDs over the past two decades (e.g. encumbrance and optical enhancements) which could enable HMDs to see wide adoption on the business and commercial flight deck in the near future.

The overall statistical reporting quality of experiments included in the current review was lacking. For example, of the three studies that reported a HMD related performance advantage only one validated the finding with a statistical analysis. Furthermore, where experiments did provide a statistical analysis, not one included the associated effect size. While it might be expected that the effect size of an analysis comparing different display formats (e.g. tracking performance with a HMD versus and head-down display) at this stage of the technology's maturity will yield large effect sizes, the evaluation of more mature HMD concepts will undoubtedly depend upon detecting effect sizes that are far smaller. An example, determining the optimal set size and organization of HMD symbology in a way that does not risk operational safety by inducing attentional tunneling. Technically, this could be difficult to achieve with the mid-level fidelity requirements (e.g. collimated displays) that were used in the majority of experiments reviewed in this paper. A potential solution to this obstacle could be the implementation virtual reality (VR) as a lower fidelity platform to support the evaluation of future HMD 3D conformal symbology concept prototypes.

The studies reviewed in the current paper present a promising foundation of HMD human factors research. Future research will require a greater emphasis on the evaluation of how 3D conformal symbology presented on a HMD can support pilot performance, and enhance safety and efficiency of across a greater range of flight phases. In particular, minimum symbol sets should be derived for each phase of flight and any additional information presented should be justified against well-defined requirements.

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