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The retrofitting of a cockpit with a Head-Up-Display (HUD) raises potential accommodation and perceptual issues for pilots that must be addressed. For maximum optical efficiency, the goal is to be able to place every pilot's eye into the HUD Eye Motion Box (EMB) given a seat adjustment range. Initially, the Eye Reference Point (ERP) of the EMB should theoretically be located on the aircraft's original cockpit Design Eye Point (DEP) while horizontal and vertical seat adjustment would allow pilots to position their eyes inside the EMB. However, human postures vary, and HUD systems may not be optimally placed. In reality there is a distribution of pilot eyes around the DEP (which is dominant eye dependent) therefore this must be accounted for in order to obtain appropriate visibility of all of the symbology based on photonic characteristics of the HUD. Pilot size and postural variation need to be taken into consideration when positioning the HUD system to ensure proper vision of all HUD symbology in addition to meeting the basic physical accommodation requirements of the cockpit. The innovative process and data collection methods for maximizing accommodation and pilot perception on a new "tactical airlift" platform are discussed as well as the related neurocognitive factors and the effects of information display design on cognitive phenomena.

In commercial aviation 983 accidents occurred between 1980 and 2007, involving multiengine jet aircraft that weighed 12,500 pounds or more with cockpits that did not contain HUDs (Flight Safety Foundation, 2009). From information obtained in flight simulators, it is believed that up to 73% of those accidents could have been prevented had a HUD been installed in the cockpit (Flight Safety Foundation, 2009; Kim, 2009). That study made those estimations with the assumption that the HUD was optimally placed in the cockpit. It also assumed that the HUD EMB is matching the Cockpit DEP, and is within the pilot Line-of-Sight (LOS), which often times is not the case once the HUD system is actually installed in the aircraft, especially if it did not originally come with a HUD (Hudson, Zehner, Harbour, & Whitehead, 2011). A method should be established to ensure that the HUD is ideally spatially located in the cockpit to reduce pilot workload and increase situation awareness (Harbour, Christensen, Estepp, & Gray, in press).

## PURPOSE

The purpose of our study was to conduct an initial anthropometric and ergonomic cockpit assessment in order to measure the pilot interface with cockpit functions. This study specifically mapped real Pilot and subject Eye Box locations in the cockpit and the HUD Pilot Eye Motion Box for the prototype HUD installation. Both were digitized using a FARO arm, which was also used to reverse engineer the entire cockpit and put into Computer Aided Design (CAD) software. These geometric data are necessary to consider the perceptual effects onto mental Workload (WL) and Situation Awareness (SA).

## METHODOLOGY

This study served as a "first look" to assess the major accommodation problems associated with a HUD installation. A complete accommodation evaluation that determines a percentage accommodation for the flying population, and which also quantifies reach and clearance minimums and maximums, will be done at a later date. For this study, five women and fifteen men were selected based on their Sitting Eye Heights, which ranged from 29.2" to 35.0," covering the entire male range and most of the female range reported in the Aircrew Sizing Survey (ACSS, Table 1 below).

| Table 1. USAF Aircrew Sizing Survey: 2009-2011 | | | |
|---|---|---|---|
| SITTING EYE HEIGHT | Mean | 5th %ile | 95th %ile |
| Males | 32.4" | 30.5" | 34.4" |
| Females | 30.4" | 28.3" | 32.2" |

Their Mid-Pupil location was mapped in 3D Space with a FARO arm after he or she visually "lined up" on original cockpit "design eye spheres" (hence, they were positioned at their perceived DEP). In addition, seat position and eye location for the four in-aircraft qualified pilot subjects were recorded where he or she would actually fly. Seat positions were recorded (as adjustment notches Back and Down from "FULL UP AND FORWARD"). Pilots will need to place their eyes inside the HUD EMB to accurately see 100% of the HUD symbology. If pilots need to move from their normal seat position, accommodation problems (eg. clearance and/or reach problems) could occur (Hudson, Zehner, Harbour, & Whitehead, 2011). To maximize the ecological validity of this study, all data collection was accomplished in an actual aircraft cockpit on the airport tarmac where actual flight operations occur (Figures 1 and 2). To avoid disrupting the subject's normal habit patterns in the cockpit, experimenters did not direct the methods that a pilot would use to control the aircraft. Consequently, this study is a quasi-experimental design.

**Figure 1.** FARO Arm mounted in co-pilot position after seat removal.

**Figure 2.** Installed FARO Arm for cockpit and subject digitization.

**Participants and Procedures**

*Participants.* Nineteen participants were recruited from the Great Lakes region and ranged in ages from 20 to 60. Seven of the participants had flying experience and four were qualified in the aircraft. Participants occupied the pilot position using both the Heads Down Display (HDD) and HUD for ground testing. The test plan was reviewed and approved by the Aeronautical Systems Center's Technical Review Board. As the study was part of normal duties, no additional compensation was provided.

*Tasks.* Each test case was outfitted with and without operational gear. Each subject's accommodation was evaluated in the cockpit: internal field of view (IFOV), external over the nose (OTN) vision, reach to controls, overhead clearance, and egress (where required). HUD FOV (HFOV) was also evaluated.

*Equipment.* The military aircraft had an L-3 Communications HDD and a Rockwell Collins Flight Guidance Systems HUD. The digitized data were collected using a FARO Arm system (up to 0.0007" accuracy), which included a cockpit mountable 3-D laser data collection system.

*Procedures.* Reach measurements were taken on subjects reaching to the landing gear handle, and the upper, middle, and lower central main instrument and computer panel switches. This was done with and without straining (shoulder, arm, and leg muscles) against a locked shoulder restraint system. Control authority (Yoke, Rudders, and Throttles) was also measured and assessed. Nose wheel steering was not tested. Subject seat positions associated with optimum HUD EMB position, were compared to the mapped accommodation results (Rudder authority, Yoke Pitch and Roll Clearance, etc.) which were recorded throughout the seat position range. A Pass / Marginal /Fail, (coded GREEN / YELLOW / RED) were assigned on these issues.

*Definitions.* **Cockpit Design Eye Point (Cockpit DEP).** Spatial location and pilot position where the pilot should sit in order to operate the aircraft for optimal visibility both inside and outside, have optimal aircraft controllability and cockpit reach, and proper outside visibility to Take-Off, Fly, and Land the aircraft safely in the way it was designed, while accommodating the pilot population. Theoretically, the adjustment mechanisms for the seat and the rudders would offer accommodation for the variation in pilot body size and proportion. A set of design eye spheres, two per side, (Figure 3.) were located adjacent to the clock, above the glare shield, to aid the pilots in acquiring an eye position on Cockpit DEP.

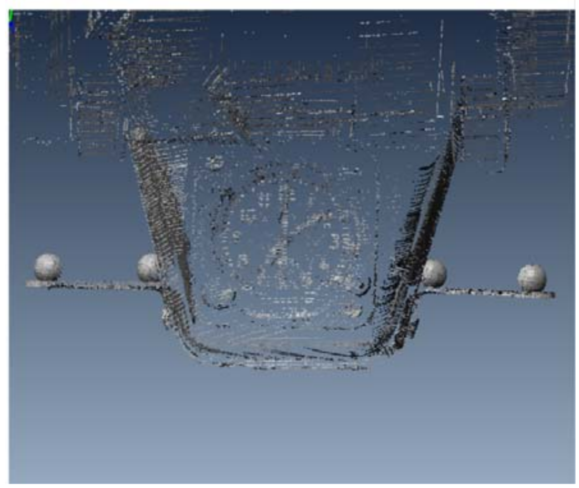

**Figure 3.** Digitized Cockpit "Design Eye Spheres."

**HUD Eye Motion Box (HUD EMB).** A three-dimensional envelope within which the pilot's eyes need to be in order to accurately see 100% of the symbology. **Total Field of View (TFOV).** The spatial angle in which all of the the symbology can be displayed / viewed measured laterally and vertically. **GREEN** – No control interference. **YELLOW** – Some control interference may occur but pilot is able to move leg/s out of the way and or is still able to move controls even if they are impacting gear. However, it complicates control of the aircraft and may delay required inputs and may still have lost up to last 5% of control authority. **RED** – Significant control interference occurs and movement of controls are impeded (limits control authority). Approximately up to last 30% of pitch aft control authority is lost and up to 30% of bank authority is lost (subject dependent).

## RESULTS

The pilot and copilot Cockpit DEP locations were reverse engineered from the design eye spheres using the FARO Arm, and were located relative to the rest of the digitized geometry using an arbitrary Cartesian coordinate system (x, y, z). This was necessary because: 1) the cockpit dimensional drawings were not available, and 2) the geometric justification for HUD system placement was not known. The TFOV and HUD EMB Center were mapped utilizing actual subject pupil locations and the FARO Arm (Figure 4).

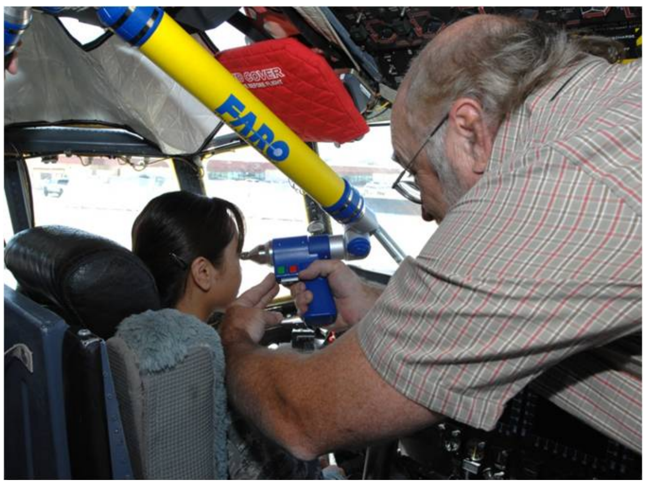


**Figure 4.** Digitizing Subject Eye Location.

All subject specific location differences between mid-pupil at "Perceived DEP" and at HUD Eye Motion Box center was geometrically calculated. These optical differences could be virtually used to translate a subject into a seat position where the subject would sit to place his or her Mid-Pupil at the HUD Eye Motion Box Center, where other accommodation issues could be addressed.

It was found that for the installed HUD, the Cockpit DEP & HUD EMB did not match; represented by an average vertical distance difference of ~2 inches (range of 1.6 to 3.25 inches), (Figures 5 and 6). Therefore, this reduced visible HUD symbology resulted in a minimum loss of 25% to as much as a 100% loss depending on pilot perception of DEP.

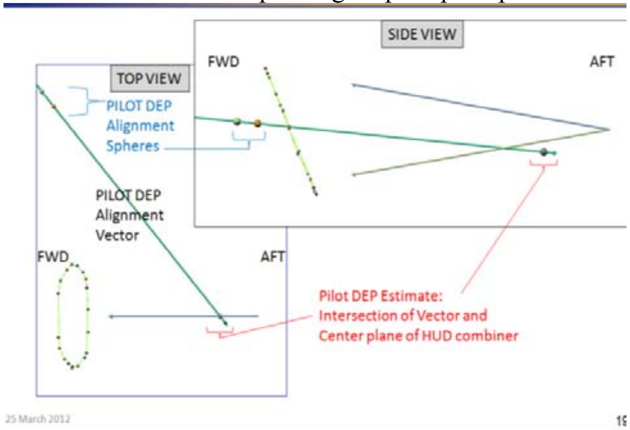


**Figure 5.** Defining the Cockpit Design Eye Point for Pilot side using the original Design Eye Spheres.

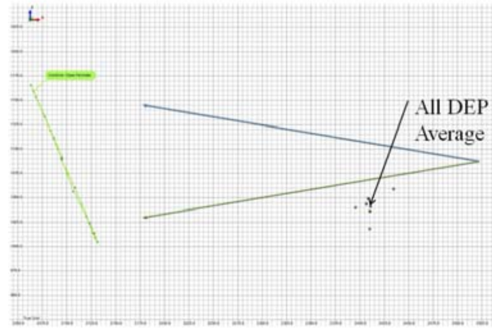


**Figure 6.** Average of Cockpit DEP locations calculated from six different pilot stations and three different aircraft superimposed with HUD EMB. (Pilot side view with Combiner and Aircraft Nose to left.)

The HUD symbology (Figure 7) loss was measured and mapped when mid-pupil was outside of HUD EMB and TFOV. The percentage of symbology lost (½" out, 1" out, etc.) is mapped below in Figure 8. Although pilots are known to do it, "Head Tilting" is not considered when writing specifications or quantifying accommodation.

**Figure 7.** View of combiner when sitting in CDEP with a 25% loss of visible symbology (most common). Some subjects experienced a total loss of visible symbology.

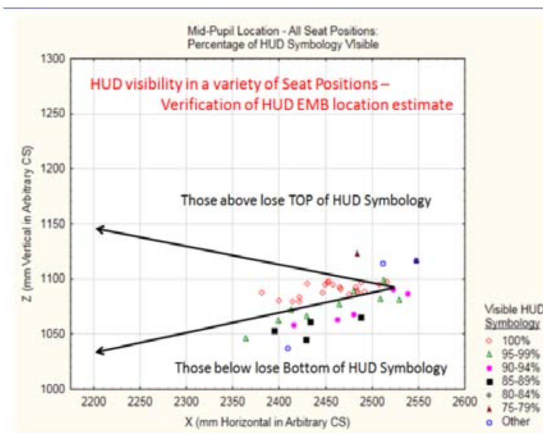


**Figure 8**. Percentage of HUD symbology visible outside of HUD EMB. (Pilot side view with HUD Combiner on left.)

To illustrate using subject photographs, below in Figure 9, a subject of average pilot eye height, is seated so his eye is at Cockpit DEP. Figure 10, indicates the extent of needed head tilt and neck stretch to place his eye into a position to use the HUD symbology.


**Figure 9.** Subject placed at Cockpit DEP. Eye is below and aft of HUD EMB center.


**Figure 10.** Subject placed at Cockpit DEP and then asked to move his head in order to see the HUD symobology.

## DISCUSSION

The mismatch of the prototype HUD EMB and the Cockpit DEP (i.e. HUD EMB Center relatively ~2" higher and ~1" forward) directly impacts accommodation. A raised seat to place a pilot eye in the HUD EMB will create yoke interference (Figure 11), as well as longer reaches to rudders and controls downward. Conversely, if the pilot remains at Cockpit DEP, the loss of visible HUD symbology results in at least 25% (above, Figure 5) and as much as a 100%, depending on the pilot's eye positioning, which is based on their perception of the Design Eye Sphere visual line.

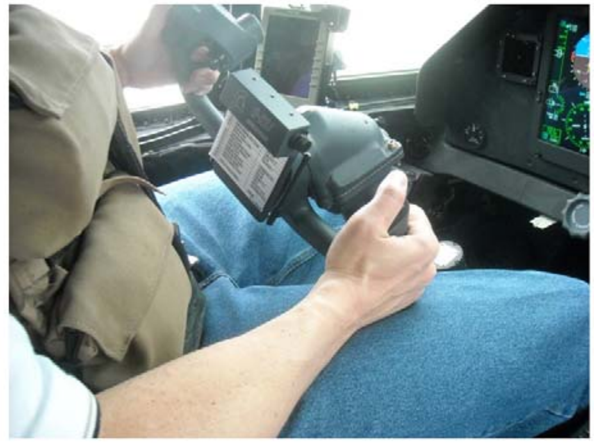

**Figure 11.** Yoke control interference was SEVERE when subject eye was placed in HUD Eye Box - 18 out of 19 subjects FAILED (with Survival Vest on).

This optical point discrepancy restricts the pilot population while potentially increasing Work Load (WL) and potentially decreasing Situational Awareness (SA) (Figures 12 and 13). Ultimately, the mismatch reduces mission capability, effectiveness, and safety.

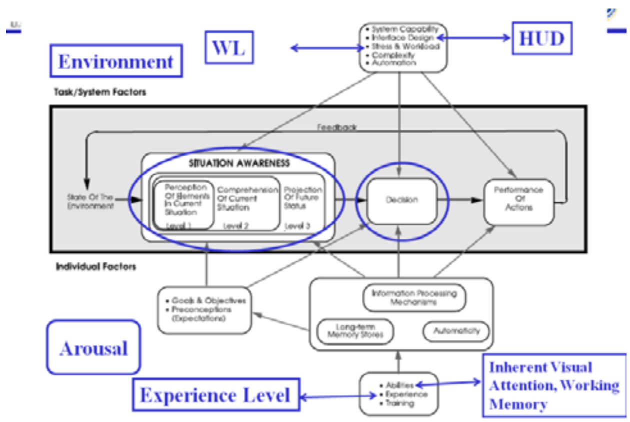


**Figure 12.** Theoretical Model of SA (adapted from Endsley, 1995b). Items in blue are additional considerations added by Harbour.

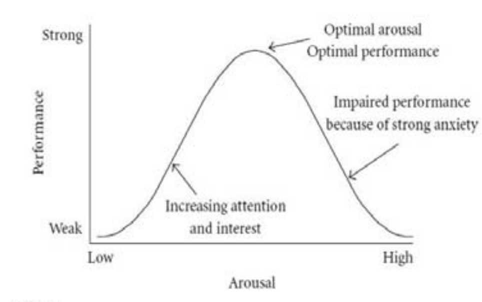


**Figure 13.** Effect of Arousal on Performance. Yerkes & Dodson, 1908. The cognitive neuroscience factors forming SA and contributing to WL, which could be affected by the spatial location of the HUD.

***Recommendation I:*** Install HUD combiner and projector spacers in order to approximately match CDEP and HEMB. This was implemented.

***Recommendation II:*** Given enough time, develop a new HUD prototype that given more data and a larger TFOV will exactly match CDEP and HEMB. This is being implemented.

The authors note that their own observations of subjects in the pilot position while seated at Cockpit DEP would need to strain their neck in order to see HUD symbology and then **also** have to look down approximately 40 degrees in order to see the HDD PFD, in order to cross-check what was seen in the HUD. This is bound to increase physical fatigue, and mental workload, in addition, creating potential issues due to the pilot's attention switching back and forth between the HUD and the HDD. Not all of the PFI on the HUD is visible due to the HUD EMB and Cockpit DEP mismatch, creating a time disruption in the interpretation of attitude information or other PFI and the effect of such transitions on pilot SA is unknown.

**Impact to Accommodation:**

The mismatched eye positions of HUD and Cockpit DEP not only potentially increases Work Load (WL), and potentially decreases Situation Awareness (SA), but it also reduces mission capability & effectiveness. In Figure 14, below, a qualitative assessment, based on our subject anthropometry, compares control authority for Yoke and Rudder while sitting at the current HUD EMB to that of the Cockpit DEP while the required armor vest is worn, both with and without the survival vest.

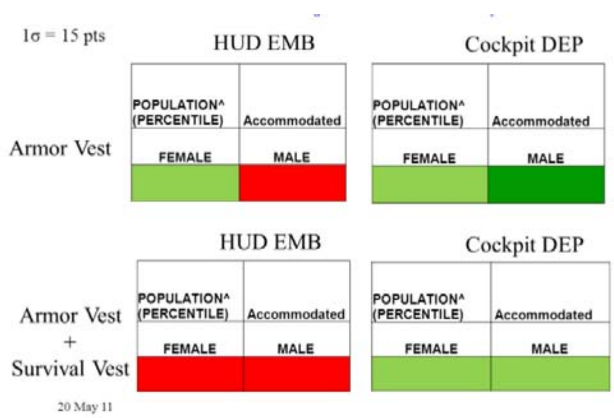


**Figure 14.** Adverse impact to accommodation (Yoke and Rudder authority) as a function **of a more forward and higher** HUD EMB as compared to the CDEP (Red is "no-go" and Green is "go"). Results for subjects wearing Armor Vest with and without Survival Vest are shown.

Lowering the HUD system in order to allow HUD EMB to match Cockpit DEP (Figure 15) would yield the best case scenario for mission success and safety, and best aircraft controllability.

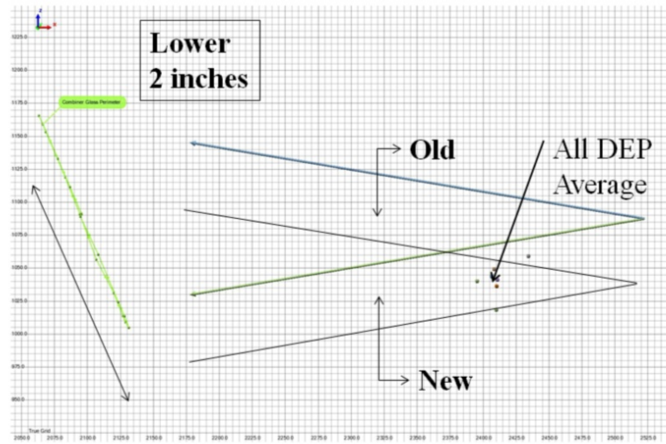


**Figure 15.** Entire HUD system needs to be lowered 2 inches to match HEMB and CDEP.

**Figure 16.** Pilot-Author with eye at Cockpit DEP and below HUD EMB.

## CONCLUSIONS

The results presented here indicate that a method should be established to ensure that the HUD is ideally spatially located in the cockpit to accommodate pilots and potentially reduce pilot WL and increase SA, which is the intent of the HUD. This study presents such a method even when cockpit drawings and HUD system optical characteristics are not known by sampling the pilot population and digitizing pupil locations, and the cockpit and HUD geometry. More research in this area needs to be accomplished, blending ergonomics, optics, and cognitive neuroscience in the actual aircraft in-flight. Neuroergonomics is a new field that integrates research between psychology, cognitive neuroscience, engineering, and ergonomics (Parasuraman, Christensen, & Grafton, 2011). The effects of varying spatial locations of information displays (ID) in addition to individual differences in visual perception and attention coupled with the effects on pilot WL and SA should be researched next (Harbour, Christensen, Estepp, & Gray, in press; Tsang & Vidulich, 2006; Wickens & McCarley, 2008).

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