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Operational Human Factors Considerations for Head-Worn Display (HWD) Usage in Civil Aviation

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12. Abstract

Advanced visual display systems, such as Head-Up Displays (HUDs), Helmet-Mounted Displays (HMDs), and Head-Worn Displays (HWDs), have been used in military aviation since the 1960s and have been increasingly introduced in general and commercial aviation cockpits. The evolution of in-cockpit technology has ushered in fundamental changes in how pilots receive and process flight-relevant information. Flight operations proceed very differently in cockpits outfitted with traditional head-down display (HDD) configurations compared to those that support viewing/interacting with HUDs, HWDs, and other types of advanced visual displays. The physical and cognitive demands placed on pilots are also impacted by the use of these technologies. Therefore, it is important to understand the nature of these interactions, the demands imposed, and the implications of display system features for safe and effective aviation, communication, and navigation. This report details a hybrid narrative and systematic literature review of human factors issues related to aviation applications of HWDs and other advanced visual displays. It summarizes the scientific findings of studies on HWD usage and compiles evidence that can inform recommendations for the usage of HWDs in civil aviation.

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List of Abbreviations

Acronym	Abbreviation Explained
ACFS	Advanced Concepts Flight Simulator (ACFS)
AFFTC	Air Force Flight Test Center
AM-LCD	Active Matrix Liquid Crystal Display
ASRA	National Research Council’s Advanced System Research Aircraft
BOSS	Brown Out Symbology System
cd/m^2	Candela per Square Meter
CFIT	Controlled Flight into Terrain
CR	Contrast Ratio
CRT	Cathode Ray Tube
cy/mr	Cycles per Milliradian
DLP	Digital Light Processing
DMD	Digital Micromirror Device
EFVS	Enhanced Flight Vision Systems
EM	Electromagnetic
EMM	Electronic Moving Map
FAA	Federal Aviation Administration
fL	Foot-lamberts
FOV	Field of View
FP	Flat Panel Technologies
GA	General Aviation
GPS	Global Positioning System
HDD	Head-Down Display
HDTS	Helmet Display Tracking System
HEMS	Helicopter Emergency Medical Service
HITS	Highway-In-The-Sky
HMCS	Helmet-Mounted Cueing System
HMD	Helmet-Mounted Display

HUD	Head-Up Display
HWD	Head-Worn Display
ILS	Instrument Landing System
LCoS	Liquid Crystal on Silicon
LED	Light-Emitting Diode
MASPS	Minimum Aviation System Performance Standards
NASA	National Aeronautics and Space Administration
NASA LaRC	NASA Langley Research Center
NASA-TLX	National Aeronautics and Space Administration - Task Load Index
OLED	Organic-LED
OKCR	Opto-Kinetic Cervical Reflex
OTW	Out-the-Window
RFD	Research Flight Deck
RMS	Remote Maintenance Subsystem
RMSE	Root Mean Square Error
SA	Situation Awareness
SA CAT I/II/III	Special Authorization Category I/II/III
SART	Situation Awareness Rating Technique
SME	Subject Matter Expert
SSQ	Simulator Sickness Questionnaire
SV	Synthetic Vision
SVS	Synthetic Vision System
TA	Tonic Accommodation
USAFSAM	United States Air Force School of Aerospace Medicine
VE	Virtual Environment
VISTAS	Visual Imaging Simulator for Transport Aircraft Systems
VR	Virtual Reality
VRD	Virtual Retinal Display

Abstract

Advanced visual display systems, such as Head-Up Displays (HUDs), Helmet-Mounted Displays (HMDs), and Head-Worn Displays (HWDs), have been used in military aviation since the 1960s and have been increasingly introduced in general and commercial aviation cockpits. The evolution of in-cockpit technology has ushered in fundamental changes in how pilots receive and process flight-relevant information. Flight operations proceed very differently in cockpits outfitted with traditional head-down display (HDD) configurations compared to those that support viewing/interacting with HUDs, HWDs, and other types of advanced visual displays. The physical and cognitive demands placed on pilots are also impacted by the use of these technologies. Therefore, it is important to understand the nature of these interactions, the demands imposed, and the implications of display system features for safe and effective aviation, communication, and navigation. This report details a hybrid narrative and systematic literature review of human factors issues related to aviation applications of HWDs and other advanced visual displays. It summarizes the scientific findings of studies on HWD usage and compiles evidence that can inform recommendations for the usage of HWDs in civil aviation.

Introduction

Advanced visual display systems, such as Head-Up Displays (HUDs), Helmet-Mounted Displays (HMDs), and Head-Worn Displays (HWDs), have been used in military aviation since the 1960s and have been increasingly introduced in general and commercial aviation cockpits. The evolution of in-cockpit technology has ushered in fundamental changes in how human pilots receive and process flight-relevant information. Flight operations are very different in cockpits outfitted with traditional head-down display (HDD) configurations compared to those outfitted with HUDs, HWDs, and other forms of advanced visual display. The physical and cognitive demands placed on the pilots are also impacted by using these technologies. Therefore, it is important to understand the nature of these interactions, the demands imposed, and the implications of display system features for safe and effective aviation, communication, and navigation.

This report details a hybrid narrative and systematic literature review of human factors issues related to aviation applications of HWDs. It summarizes the scientific findings of hundreds of articles on HWD usage, compiling evidence of human factors that can inform recommendations for the usage of HWDs in civil aviation. This report is intended to serve two primary purposes: (1) to provide an organized operational reference and evidence-based minimum recommendations for the use of HWD technologies in civil aviation aircraft cockpits; and (2) to provide a synthesis of the body of literature on operational human factors issues concerning the use of HWD technologies in the cockpit. The synthesis can then be consulted to identify research gaps and targets for future aviation research.

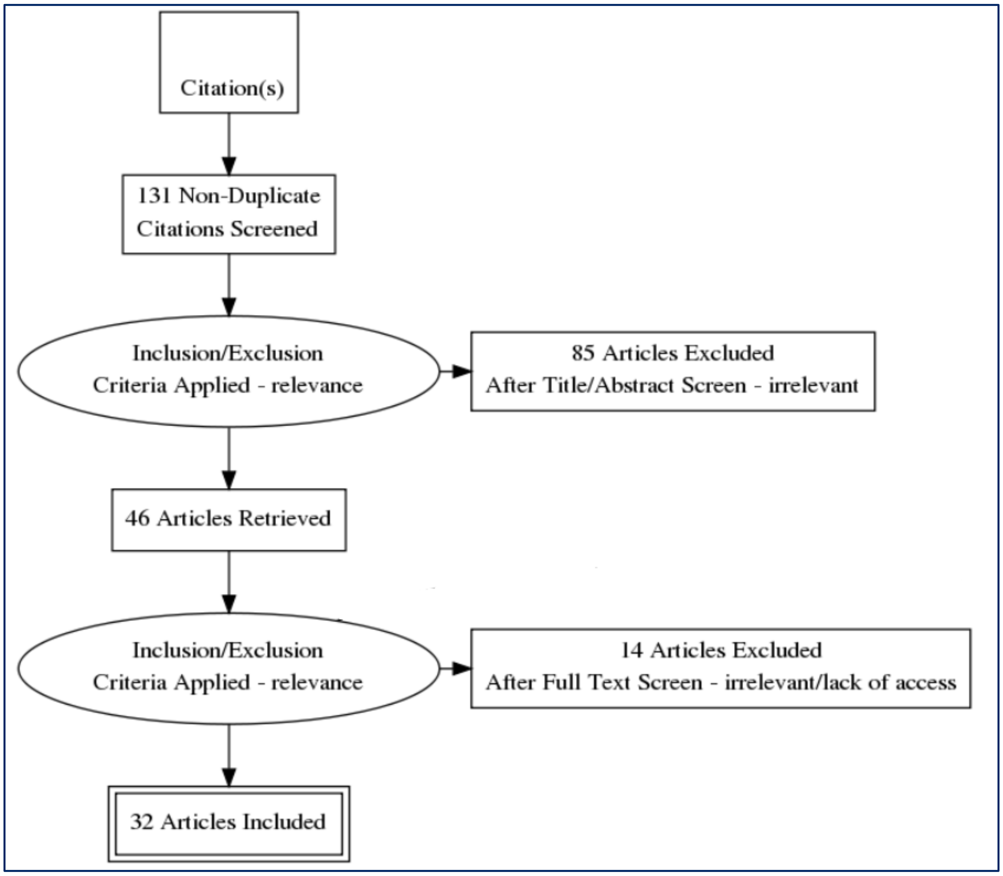
This report is intended to provide guidance on the usage of HWD technologies in civil aviation. The report includes relevant references to human factors evaluations of HWD usage in any category or class of aviation. Additionally, the report includes potential operational issues pilots may face while using advanced visual sensor and display technologies, such as Enhanced Flight Vision Systems (EFVS), that are commonly displayed via HMDs, HUDs, or similar display hardware. It should be noted that the majority of the body of literature—and thus the majority of material in this report—focuses on HUD technologies, as HMDs are not yet common in civil aviation. Indeed, the research that used specifically HMDs draws heavily from research in military aviation contexts, which often involve different task responsibilities, priorities, and workloads than in civil aviation. The authors consulted extensively with subject matter experts (SMEs) to extract relevant findings from this body of literature that apply to the usage of HWDs in civil aviation.

The report is structured to first familiarize the reader with HWD systems and the key system elements that are relevant for the subsequent introduction of human factors issues. Next, the report describes the synthesized findings of the literature regarding the general cognitive and physical human factors that are relevant for using HWDs in civil aviation. Finally, findings specific to flight contexts—such as taxi, takeoff, approach, and landing—that involve specific types of pilot information processing and control task responsibilities are organized according to context. The final section includes a discussion of performance measures and other assessment metrics that are typically used in human factors evaluations with advanced display systems. These studies can provide insight into sensitive measures for evaluating the performance and safety aspects of HWD usage during these operations and additionally support estimating the magnitudes of the effects of these human factors issues on flight performance and safety.

Method

The coordination and pacing of this review followed a structured process. The PRISMA process was used to conduct the literature review (see Figure 1). First, a substantial base of literature concerning evaluations of advanced visual displays in aviation contexts was collected and stored in a local online repository. Most of the initial literature came from a reference list compiled by Federal Aviation Administration (FAA) SMEs and from consulting with aviation safety advocacy groups. An additional set of approximately 50 relevant articles was added by the research team members, drawing from their broad knowledge in aerospace human factors engineering, pilot training, and assessing human performance with various interface and display technologies. In total, 275 articles were obtained via publicly available and subscription-based publication outlets.

Figure 1
PRISMA Diagram of Systematic Process for Identifying the Set of Articles Specific to Flight Contexts of Interest



These articles were then stored electronically in an online repository, which was used to coordinate the review efforts among the research team. The article titles and abstracts were reviewed for relevancy to the research question. Reviewing the article titles and abstracts allowed the researchers to identify relevant articles for inclusion and to categorize relevant articles into topical categories. The categorization of relevant articles was reviewed and revised as needed via regular meetings between the researchers and the FAA SMEs. Finally, the set of articles in the online repository was sorted into relevant categories.

The FAA SMEs identified additional relevant topic areas to include in the literature review during the regular meetings. Included in this addition were research publications specifically evaluating pilots' usage of EFVSs in certain phases of flight, including taxi, takeoff, and approach and landing scenarios. An additional 32 articles were included in the review.

A systematic review search methodology consisting of three stages was employed in an attempt to capture all relevant literature that specifically targeted these flight phases/contexts. First, relevant keywords were identified through group review of existing terminology/themes and group ideation and consultation with FAA SMEs. Among the key terms were technology-based phrases, such as 'enhanced [flight] vision systems', 'synthetic vision systems' (SVS), 'HWD', 'HUD', 'HMD', and common synonyms for these terms. This search emphasized specific operational contexts or themes in the keyword search string. Table 1 shows the themes that were combined with the keywords to search for articles.

Table 1
List of Search Themes and Keywords Used to Systematically Review Issues with Advanced Displays in Articular Phases of Flight/Operational Contexts

Themes	Keywords
Approach Landing Takeoff Taxi	enhanced flight vision system* OR synthetic flight vision system* OR head worn display* OR helmet-mounted display* OR head*-up display*

The themes and identified keywords were used to search within several scientific databases spanning diverse scientific fields in order to minimize the chances of missing any published or publicly available articles or reports. The searches were limited to the English language and published between 1950 and 2018. This broad keyword search resulted in 131 titles identified in consultation with SMEs that reviewed early drafts of this report. Additional impactful sources published between 2018 and 2020 were identified, and these sources were added to the review where appropriate.

For the second step of the review process, the abstracts or executive summaries of the 131 articles were screened for relevance by the research team. Articles were eliminated from consideration if they were deemed to have little or no relevance to the current effort. Removed articles included those that did not concern the targeted flight contexts, those primarily focused on the design of the technologies (and did not include human user evaluations), and those that evaluated the usage of the technologies for purposes other than supporting the pilot performance of aviation and navigation tasks (such as pilot monitoring).

Following the screening of abstracts, the next step in the systematic review process included reading each of the remaining 46 articles. Each article was read in its entirety by members of the research team. Key human factors issues and performance measures from each paper were noted and incorporated into the report. Redundant versions of work published in multiple outlets and articles deemed to have very low relevance after the full review were removed at this point. This left 32 articles identified systematically to include in the review synthesis, adding to the initial repository collection of 275 articles. We reviewed 307 articles, and ultimately, 187 were deemed to be unique contributing articles and are included in the synthesis. This review synthesizes information concerning operational human factors with advanced visual display systems—HUDs, HWDs, HMDs, and night-vision goggles—in aviation cockpits. While the vast majority of the research with these systems is conducted in military aviation contexts, the emphasis of this review is to examine the current and potential human factors issues that can result from implementing these technologies in civil aviation.

Literature Review Summary: Fundamentals of Advanced Visual Display Systems

The term HWD is broadly applied to advanced visual displays that typically:

- Can be worn on the head without interfering with other necessary equipment (such as pilot headsets),
- Are lightweight, relatively unobtrusive, and require little in terms of physical demand to operate, and
- Convey data that may be conformal to external real-world visual sources.

HMDs support modes of human interaction similar to those supported by HWDs and have similar human factors issues that must be considered. HMDs have been investigated in military contexts for several decades (i.e., Wells et al., 1989; Winterbottom & Pierce, 2006; Yeh et al., 1998). With more recent technological advances and decreasing development costs, HWDs are increasingly available for commercial aviation operations (Arthur et al., 2014; Arthur et al., 2015; Baber, 2001; Bachelder & Hansman, 1996; Cupero et al., 2009; Edgar, 2007; Edgar et al., 1993; Grunwald & Kohn, 2003; Shelton et al., 2015; Wille et al., 2013), thus providing a substantial body of literature for operations in those domains.

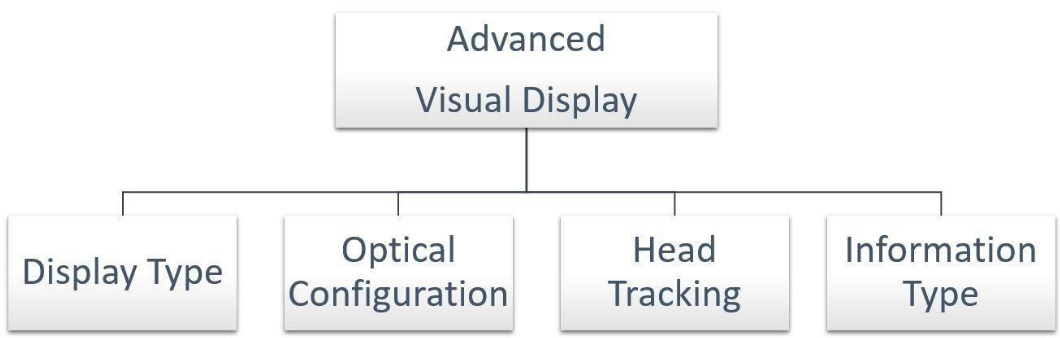
Similarly, HUDs project operationally relevant visual information onto the operator's forward FOV at some focal distance beyond the workstation (Weintraub & Ensing, 1992). They are not worn by the pilot, but from a human factors perspective, they share many of the same benefits and limitations as HWDs. Like HWDs, HUDs allow a pilot's head to remain "up" to maintain visual contact outside of the aircraft while simultaneously providing awareness of other visually displayed data sources. In aviation, HUDs are normally conformal to the outside world or outside window. The conformal display has the ability to superimpose information on real-world landmarks; in other words, the virtual imagery overlays a real object, such as the virtual horizon line of a pitch ladder superimposed on the real horizon (Weintraub & Ensing, 1992).

Advanced Visual Displays

Advanced visual displays, such as HMDs and HWDs, can be described as having an information or image source, “collimated” optics in a head mount, and a visual coupling system (Melzer & Moffit, 2001; Rash et al., 1998). Collimated optics result in light rays from the image source being projected parallel to each other, making the virtual image appear to be at optical infinity.

Figure 2 presents a block diagram of four major elements of the HWD and HMD advanced display systems: display type, optical configuration, head tracking, and display information type (Patterson et al., 2006). Display type refers to the hardware that generates imagery corresponding with sensor data (Rash et al., 1998). The input sensor data could originate from numerous sources, such as global positioning system (GPS), cockpit instrumentation, weather reports, and multispectral video imagery. The optical configuration sizes and focuses the imagery to achieve the desired visual experience when the imagery is viewed by one or both eyes (Rash et al., 1998). The head-tracking system detects the position and movement of the user’s head and can synchronize the movement of imagery with head movements. Finally, a variety of information types, such as static or dynamic symbology, text and graphics, and virtual and real-time imagery, can be included in the display space (Patterson et al., 2006).

Figure 2
Major Elements of Advanced Visual Displays Such as HWDs and HMDs



Display Hardware

The display hardware can be divided into three categories: cathode ray tube (CRT), flat panel technologies (FP), and laser (Rash et al., 1998). Flat panel technologies include digital light processing (DLP), liquid crystal displays (LCD/Active Matrix Liquid Crystal Display [AM-LCD]/Liquid Crystal on Silicon [LCoS]), light-emitting diode (LED), and virtual retinal displays (VRDs). An important consideration for selecting the visual display hardware is the Field of View (FOV) required based on the tasks performed by the pilot (Cakmakci & Rolland, 2006); some pilot tasks are best supported by a large FOV (around 70 degrees; de Vries & Padmos, 1998). The advantages and disadvantages of each of these displays are listed in Table 2.

Table 2
Advanced Visual Display Hardware Advantages and Disadvantages

Display Type	Advantages	Disadvantages
Cathode Ray Tube (CRT)	High luminance output, inexpensive cost of hardware, durability, desirable temporal characteristics	Heavy, large, high power requirements and thus higher operational costs
Virtual Retinal Displays (VRDs)	Improved resolution, contrast, brightness, and color quality, decreased weight (compared to CRT)	Eyebox restrictions for image projection on retina, scanning complexity, susceptibility in high vibration environment, and limited pupil size
Digital Light Processing (DLP); Digital Micromirror Device (DMD)	Presents good quality motion imagery	Blurring or double images possible due to illumination of pixels for entire video frame
Liquid Crystal Displays (LCoS and AM-LCD)	Fast, good light output, low power consumption, low weight, small size, relatively high resolution. They can be transmissive or reflective.	Blurring and double imagery; however, using Ferro-electric LCoS can reduce moving imagery blur. If illumination source is required, system is no longer compact.
Light-Emitting Diode (LED and Organic-LED [OLED])	Self-emissive, more compact	OLEDs have a shorter lifespan, with luminance for various colors degrading non-uniformly over time.
Laser-Based Displays	Bright laser diodes with luminance up to 900 foot-lamberts (fL) have been used for aerospace applications	Luminance greater than that used in tests—900 fL—may be damaging to the eyes, and higher luminances are also difficult to achieve in a portable device.

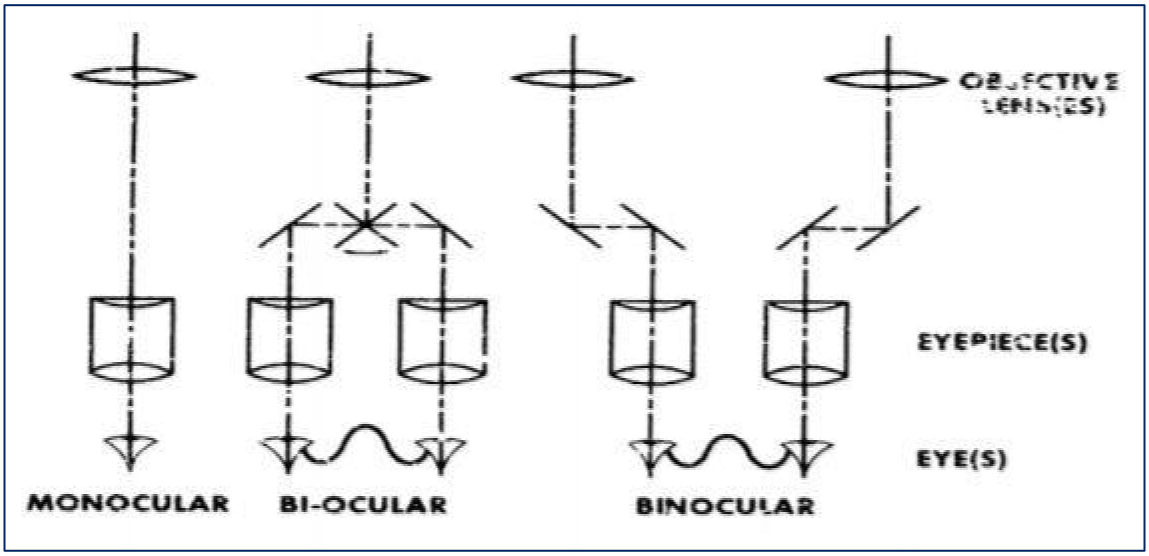
*(For more information, see Cakmakci & Rolland, 2006; Patterson et al., 2006)

Optical Configuration

Optical elements are the physical aspects of the display that impact how imagery is presented to the user, such as whether the outside world is viewable (an “open” system) or not (a “closed” system) and to which eyes the display is visible (“ocularity”). Three basic types of ocularity are described below (Patterson et al., 2006) and illustrated in Figure 3.

1. ***Monocular***: generated imagery is presented to only one eye.
2. ***Bi-ocular***: generated imagery is presented using a single image source to both eyes.
3. ***Binocular***: separate images are presented independently to each eye. This configuration can support apparent depth of synthetic imagery through binocular disparity (i.e., retinal disparity) depth cues (i.e., Wickens et al., 2004).

Figure 3
Types of Optical Configurations in Advanced Visual Displays



*(For more information, see Harker, 1972)

The choice of optical configurations for HWDs has implications for many potential human factors issues, including physical factors due to the size and weight of the system, the quality of imagery, FOV, and light transmittance (Lippert, 1990).

Head Tracking

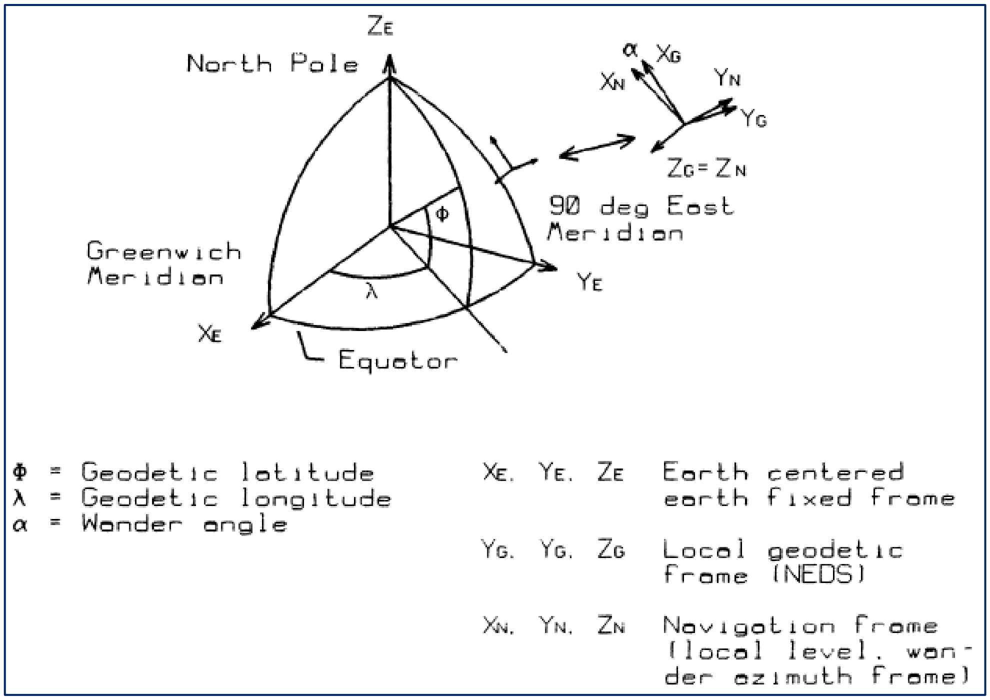
Advanced displays can use the orientation of the display to convey world-referenced information to the user via conformal visual imagery. Conformal imagery is generated in a way that “conforms” to objects of interest in the outside world in some situations by aligning the generated imagery such that it is superimposed with the background geography (Patterson et al., 2006) or by collocating synthetic imagery with visual data sources in the external world. For HWDs, head-tracking functionality can allow generated imagery to be responsive to natural movements and postural positions in order to support adequate levels of realism in the imagery. Orientation must be tracked accurately to ensure information is presented in accurate locations.

Further, a typical air vehicle has multiple applicable reference frames; it is important to specify reference frames to a pilot using an HWD. An air vehicle has at least five applicable reference frames, such as those based on the vehicle, its velocity vector, the Earth, different sensors, and those based on the operator—one reference frame for their head and another for their eyes. This poses an engineering challenge because the typical HWD can present symbology positioned in the coordinate systems of each of the reference frames (Newman & Greeley, 1995). In general, the design of aircraft displays needs to consider all potential flying movements, including unusual ones, and ensure the display supports acceptable performance.

Newman and Greeley (1995) identified nine reference frames that may be pertinent to designing an HWD:

- space or inertial frame,
- Earth or navigation frame (see Figure 4),
- body or vehicle frame,
- motion or flight path frame,
- one or more sensor frames,
- head or display frame,
- anatomical head frame,
- eye frame, and
- display frame.

Figure 4
Earth-Based Frames of Reference



*(For more information, see Newman & Greeley, 1995)

Current generations of HWD technologies integrate accelerometers to monitor head movements and adjust the apparent perspective point of the user to match the naturally expected changes in imagery presented to each eye. Typically, head trackers sense accelerations according to six degrees of freedom: three rotational (roll, pitch, and yaw) and three translational (x, y, and z). Often, a subset of these tracking dimensions is sufficient, depending on the requirements for use (Patterson et al., 2006). Table 3lists some of the most common technologies used for head-tracking.

Table 3

Common Types of Head-Tracker Technologies

Head-Tracker Technology	Notes	Recommendations	df
Electromagnetic (EM)	Affected by nearby EM radiation and metal.	For small operating spaces.	6
Electro-optical	Requires a direct line of sight and large FOV.	No instruments, switches, or displays should be located above the user's head.	6
Inertial (mini gyroscopes)	Measures high rates of head rotation.	Enclosed areas where placing additional sensors is not possible.	3

*(For more information, see Patterson et al., 2006)

Types of Information Displayed

The information being relayed by these advanced visual displays can follow several different formats, including verbal/numerical descriptors with generated text, graphical display or highlighting of spatial data, encoded symbology, and real-time video imagery (Patterson et al., 2006; Weintraub & Ensing, 1992). The imagery can aid the pilot in tasks such as visual target acquisition (Arbak et al., 1988; Craig et al., 1997), collision avoidance (Coppenbarger, 1994), ground operations (Arthur et al., 2015), and in-flight navigation (Arthur et al., 2014; Boestad et al., 1998; Dudfield et al., 1995). The manner in which information is displayed may be context-dependent, differing based on the preset mode or triggering a change in display when networked sensors sense user interactions with system controls, such as the activation of auto-pilot systems or the resumption of manual control of the aircraft.

Overall System Configuration

The design or selection of the type of HWD and its features depends on parameters such as the required FOV, required resolution, need for color display, extent of head movement available for head-tracking, and optical requirements (Cakmakci & Rolland, 2006). HWDs are designed based on the requirements of the context or domain in which they will be used. The design of advanced visual display technologies can vary significantly, presenting a broad set of human factors issues that pilots may encounter, such as mis-accommodation (Biberman & Alluisi, 1992; Edgar et al., 1993), misperception (Arthur & Brooks, 2000; Biberman & Alluisi, 1992), binocular rivalry when using monocular HWDs (Browne et al., 2010; Cakmakci & Rolland, 2006; Cupero et al., 2009; de Vries & Padmos, 1998; Laramee & Ware, 2002; Rash et al., 1999; Winterbottom et al., 2006b), spatial disorientation and simulator sickness (Arthur, 2000; Biberman & Alluisi, 1992; Cupero et al., 2009; Ehrlich, 1997; Eriksson, 2010; Kasper et al., 1997; Liggett, 2002; Morphew et al., 2002; Patterson & Winterbottom, 2007; Rash et al., 1999), and more. The human factors impacts of different components of the overall system configuration are detailed in the following section.

Human–Systems Interaction

This section reviews the different human factors considerations for using an HWD system for aviation. The general topics of the review include:

- *Visual Perception*. Human visual processes; how displays and related display elements are interpreted and comprehended.
- *Workload and Performance*. The influence of the different elements of the display and the demands they place on the human as reflected in task performance.
- *Situation Awareness*. The aiding/impeding qualities of these displays to task performance and maintaining situation awareness (SA).
- *Physical Factors*. The impact of the weight of the display or physical influences of the information displayed, leading to ill effects on the human body and overall usability.

Visual Perception

A critical concern for the use of HWDs by pilots is that they should be able to clearly view the information provided by the display while maintaining visual contact with the out-the-window (OTW) scene. The pilot’s ability to visually process both the display and the OTW scene concurrently is dependent on HWD characteristics such as ocularity (Baber, 2001; Browne et al., 2010; Cakmakci & Rolland, 2006; Laramee & Ware, 2002; Melzer, 2001; Yeh et al., 1998), as well as display qualities such as luminance and contrast (Melzer, 1997; Melzer, 2001; Winterbottom & Patterson, 2006; Rash et al., 1998; Patterson & Winterbottom, 2007). The ocularity of the system, as well as the physical size of the HWD hardware (which can be dictated to some extent by its ocularity), can restrict the OTW FOV, disrupt eye–hand coordination, and affect the perception of size and space (Baber, 2001), all of which have safety implications during flight. This section discusses the main challenges and human factors issues described in the literature that concern visual processing with HWDs. First, visual perceptual factors are introduced, followed by discussions on key visual elements of advanced displays.

Depth of Field

The depth of field or focus range is the range of distances in object space where visual stimuli are viewable in sharp focus (Patterson et al., 2006). For proper visualization, a simulator HWD needs to be in the user’s depth of field (Patterson & Winterbottom, 2007). The depth of field is influenced by the focal distance at which the HWD is located. The pilot is often required to view other displays present in the cockpit while using the HWD. Information from all the displays the pilot uses to gather task-relevant information must be clearly visible and in sharp focus. In such a case, the focal distance of the other displays must also be considered to ensure the pilot can comfortably view these displays, the HWD, and the OTW scenes. This means the focal distance of the HWD and the other displays should be similar while maintaining the visibility of the OTW visual stimuli (Patterson et al., 2006). Winterbottom et al. (2007) found the most appropriate focal distance for monocular simulated display designs is likely the midpoint between the shortest and longest viewing distances. Setting the focal distance of the HWD to optical infinity can ensure this factor will not be problematic when the pilot is simultaneously viewing virtual imagery and OTW scenery.

Luminance, Contrast, and Symbology

Depth of field can be affected by the brightness, contrast, and resolution of the symbols or images displayed on the HWD (Patterson et al., 2006). Depth of field is positively correlated with brightness and negatively correlated with resolution (Patterson & Winterbottom, 2007). In poorly lit conditions, the viewer will tend to automatically focus on the closer of two objects (Iavecchia et al., 1988). This affects both vergence (Cupero et al., 2009; Patterson et al., 2006; Patterson & Winterbottom, 2007) and accommodation (Biberman & Alluisi, 1992; Cupero et al., 2009; Edgar et al., 1993; Edgar, 2007; Patterson et al., 2006; Weintraub & Ensing, 1992). In conditions with low illuminance, the possibility of errors of accommodation is higher (Cupero et al., 2009; Patterson et al., 2006). Visual accommodation tends to rest at a distance of about 1 m from the observer (i.e., dark focus), and this is further propagated in degraded viewing conditions of stimuli like low illuminance (Patterson et al., 2006). Therefore, the color, luminance, brightness, and contrast of the symbology or imagery used in the HWD need to be accounted for based on the intended application of the display (Kranz, 1998; Rash et al., 1998; Rash et al., 1999; Rolland & Hua, 2005; Shaw, 2002). Luminance is the amount of light emitted by the display that reaches the user's eye. Pupil size varies to control the amount of light that strikes the retina. Greater luminance will reduce the pupil size, and a lower luminance will increase the pupil size to allow more light to reach the retina. However, luminance also influences the depth of focus and depth of field such that there is a luminance-resolution tradeoff (Patterson et al., 2006). An increase in luminance will cause a reduction in the pupil size and will lead to a greater depth of focus (range of distances where images are visible clearly and in focus) and an increase in resolution will lead to a smaller depth of field (Patterson et al., 2006).

Luminance contrast is an important factor that facilitates differentiation of the to-be-interpreted symbology from the background. Frey and Page (2001) found that a proper luminance contrast between symbology and background could enhance the clarity of symbology during flight operation. In a cockpit, there is usually a wide range of brightness or background luminance. Weintraub and Ensing (1992) suggested that the background luminance in cockpits varies between 0 to 8,000 fL with the luminance contrast at 1.1511 (as a minimum requirement). In poorly lit situations or when the background luminance is low, a luminance contrast ratio of 4:1 is recommended. HWD symbology with low luminance contrast can suffer from suppression effects; therefore, it is prudent to use symbology of high luminance contrast (Winterbottom et al., 2006b). With adequate luminance contrast, HWDs may be more efficient than HDDs (May & Wickens, 1995; McCann et al., 1997).

Symbology or imagery displayed on an HWD can be colored or monochrome, depending on the application. There are advantages and disadvantages associated with using either colored or monochrome symbology in aviation HWDs. Monochromatic symbology is displayed by only one phosphor and can achieve high levels of luminance output, while the usage of colored symbology is accompanied by the aforementioned tradeoff between resolution and luminance (Rash et al., 1998). Colored symbology in HUDs and HWDs has some potential advantages over monochrome symbology, such as reducing clutter in the display, capturing the user's attention, guiding the user's attention to relevant information, etc. (Dudfield, 1991; Havig et al., 2001; Post et al., 1999; Rash et al., 1998; Rosenholtz et al., 2005). Additionally, past studies show critically high error rates for certain colored symbology on certain backgrounds (Martinsen et al., 2002). Thus, those factors are required to establish their minimum and optimal requirements in order to ensure the symbology is well perceived and interpreted as intended (Martinsen et al., 2002).

Using colored symbology could be advantageous in a cluttered cockpit for organizing information (Rosenholtz et al., 2005); however, color coding may not help when used with non-important information (Dudfield, 1991). Color coding has advantages in targeting tasks and unformatted symbology (Weintraub & Ensing, 1992). However, it is important to consider the luminance contrast ratios of the symbology or imagery displayed (Havig et al., 2001; Rash et al., 1998). Martinsen et al. (2002) investigated colored symbology on a head-mounted display and showed the luminance contrast ratios for character legibility ranged from 1.09 to 1.13 on red-, yellow-, and green-colored symbology. Martinsen et al. (2002) supported the conclusion drawn from Havig et al. (2001), which found the minimum background-symbology contrast ratio ranged from 1.12 to 1.18 in order to identify colors of the presented symbology (i.e., red, yellow, or green). However, for some colored symbology to background combinations (i.e., green symbology against brick background and red symbology against green background), it is difficult to identify precisely if luminance contrast is below the minimum threshold (Havig et al., 2001). Havig et al. (2003) reported that red was the easiest color to be recognized compared to green and yellow. However, regardless of color, even out-of-focus images or images with low resolution can contribute to visual fatigue in the user (Keller & Colucci, 1998).

In another study, Post et al. (1999) investigated color coding using red, yellow, and white weapon symbology on HWDs. The effects of adding colored symbols to a specific weapon symbology were shown by having 12 volunteer military pilots from three countries fly a simulated air-to-air engagement. The HWD symbology was drawn on the dome of the simulator and superimposed additively on the OTW scene with a 20-degree FOV. It was shown that the added color coding facilitated a reduction in reaction time of between 1.24 and 1.58 s depending on the target, without a decrease in accuracy. This effect, however, could not be attributed to differences in the luminance contrast of the displayed symbology because the yellow symbols used were slightly brighter than the standard green, and the red symbols were less bright. The symbols were displayed for several seconds before firing, providing enough time for the pilots to notice them (Post et al., 1999). Dudfield (1991) found there was no effect on the addition of colors in HUD, but subjective mental workload was significantly alleviated. Finally, the retina is most sensitive at 580 nm; thus, using a color close to that frequency (like green) produces the brightest image for the least input wattage, and shorter-wavelength colors (like blue) tend to bounce around in the eyeball and appear fuzzy compared with the lower-frequency (red) colors that do not suffer so much from this effect.

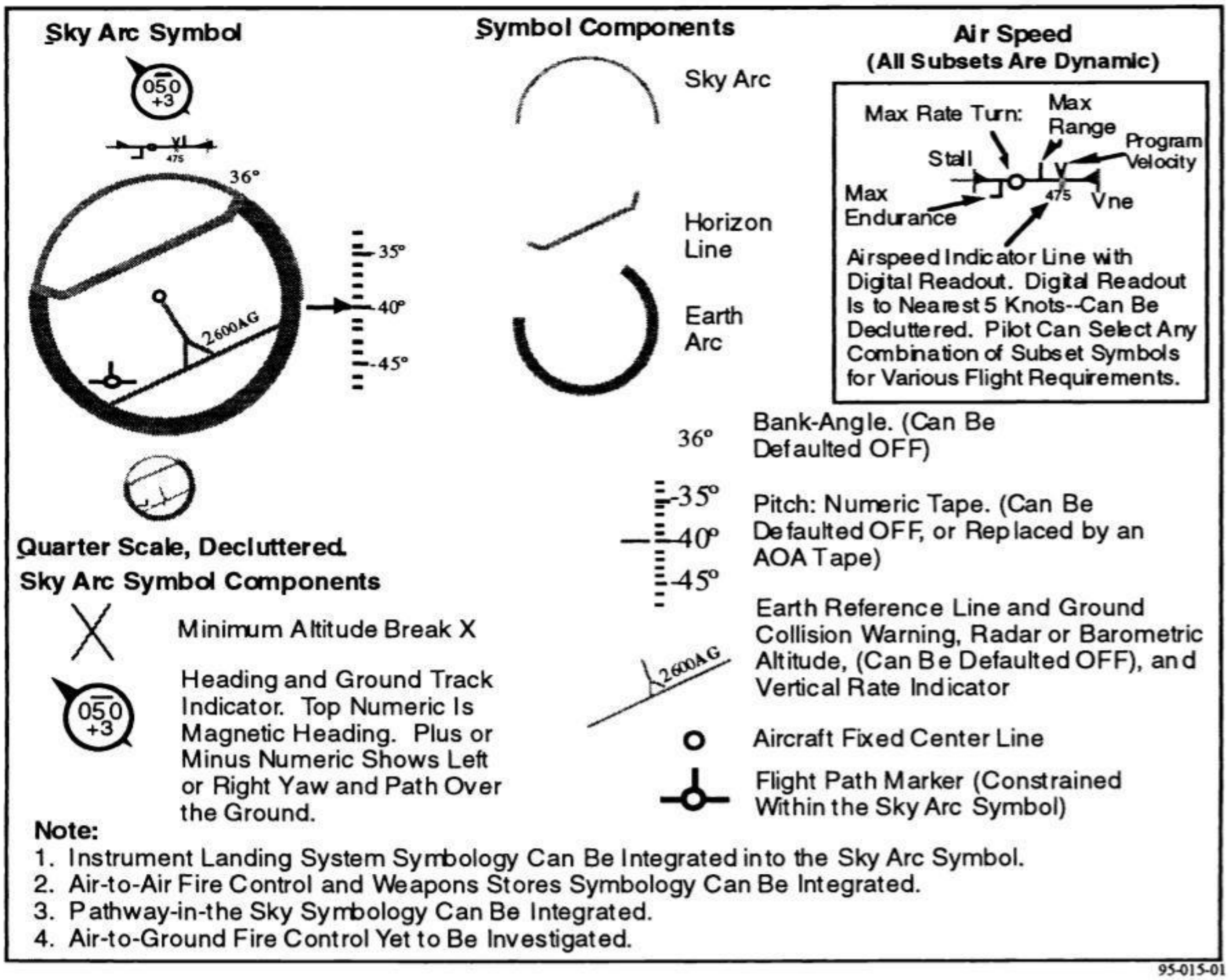
While using colored symbology may have some utility in HWDs (i.e., attention cueing), the implications of using colored symbology need to be thoroughly researched before concluding any absolute advantages or disadvantages. The symbology needs to conform to certification guidelines for the use of color in flight-deck displays.

Role in Information Processing

In complex environments such as the cockpit of an airplane, important information can be missed if the display of information is not salient enough to capture the pilot's attention. Designing attention cues into an HWD system can guide the pilot's attention to important information relevant to the task and simplify visual scanning and information search in the presence of environmental distractions.

The design of visual and multisensory cues has been shown to impact scanning patterns for pilots' information retrieval processes and reduce search times for key information associated with cues. For example, Voulgaris et al. (1995) developed the "Sky Arc" symbology for attitude control in HWDs (see Figure 5), which conveyed pitch, roll, heading, air speed, and terrain avoidance cues via different elements designed into the display. Results from this study indicate the Sky Arc was generally preferred, and pilots recovered more quickly from the simulated unusual altitude conditions when using Sky Arc compared to the standard pitch ladder symbology.

Figure 5
Sky Arc Symbology and Sky Arc Symbology Components



*(For more information, see Voulgaris et al., 1995)

Color coding of symbology may support information processing. Early research showed that incorporating color coding into symbology did not prove to be as beneficial in aviation as in other domains and was not generally recommended for flight operation (Weintraub & Ensing, 1992). However, more recent investigations found that when displayed under appropriate luminance and with the appropriate contrast, colored symbology can enhance target task performance (Post et al., 1999). Moreover, the selection of hues also influences the effectiveness of the color coding. In an experiment to determine the luminance contrast ratio required for reliable recognition of stimuli colors presented in night-vision goggles, it was determined red was more easily recognized when compared to green and yellow against the green background of the night-vision goggles (Havig et al., 2003). Due to large variations in background luminance during flight operations, it is difficult to select a set of hues that could be universally effective in the design of HWD symbology. While color can play a key role in supporting the fast localization of uniquely colorized data, the choice to use monochrome or colored symbology was found to be significant in the user's perceptions and interpretations of the information being conveyed via advanced visual displays (Martinsen et al., 2002). Table 4lists values for visual display dimensions used in empirical studies.

Table 4
Recommendations for Visual Elements

Attribute	Suggested or Recommended Value	HWD/HUD	Source
Recommended luminance for imagery	27,410.1 candela per square meter (cd/m^2)	HWD	Patterson et al., 2006
Luminance	10 fL (for night use) to an optimal 1600 fL (for day use)	HWD	Rash et al., 1999
Average outdoor luminance - recommended for HWD	2000 fL	HWD	Rolland & Hua, 2005
Luminance contrast required (monochromatic)	1.5:1	HUD	Weintraub & Ensing, 1992
Luminance contrast preferred (monochromatic)	1.522	HUD	Weintraub & Ensing, 1992
Luminance contrast (monochromatic)	1.4:1	HWD	Rash et al., 1998
Luminance uniformity tolerance between a flat field	< 20%	HWD	Rash et al., 1998
Luminance non-uniformity for a small area (monochromatic)	< 10%	HWD	Rash et al., 1998
Luminance non-uniformity for a large area (monochromatic)	< 50%	HWD	Rash et al., 1998
Luminance contrast for red color symbology - recognition	1.12:1	HWD	Havig et al., 2001

Attribute	Suggested or Recommended Value	HWD/HUD	Source
Luminance contrast for green color symbology - recognition	1.16:1	HWD	Havig et al., 2001
Luminance contrast for yellow color symbology - recognition	1.17:1	HWD	Havig et al., 2001
Luminance contrast for red color symbology - legibility	1.13:1	HWD	Havig et al., 2001
Luminance contrast for green color symbology - legibility	1.16:1	HWD	Havig et al., 2001
Luminance contrast for yellow color symbology - legibility	1.17:1	HWD	Havig et al., 2001
Luminance contrast yielded 95% correct level for colored symbology - Colored symbology	1.18:1	HWD	Havig et al., 2003
Luminance contrast - recommended for colored symbology legibility	1.09:1 - 1.13:1	HWD	Martinsen et al., 2002
Luminance contrast	1.2:1	HWD	Patterson et al., 2006
Luminance contrast - monocular HWD	Minimum Michelson level of 0.1 and HWD image should be approximately 27,400 cd/m^2, which results in a contrast of about 1.2:1	HWD	Cupero et al., 2009
Luminance contrast	The luminance of the day symbology shall be adjusted to a contrast ratio (CR) of 7:1 or less as seen by observer for the 1 fL background and greater than 1.5:1 contrast for the 3000 fL background	HWD	Rash et al., 1996
Luminance contrast - background luminance	HUD should provide a minimum luminance contrast ratio of 1.15/1 with a range of 0-8000 fL	HUD	Weintraub & Ensing, 1992
Luminance requirement	0.1 cd/m^2 - Vergence appears to be valid down to this number	HWD	Patterson & Winterbottom, 2007
Luminance requirement	6.9 - 342.6 cd/m^2 - Accommodation appears to be valid down to this number	HWD	Patterson & Winterbottom, 2007

Accommodation and Vergence

Human visual perception uses three-dimensional cues in order to determine the depth of objects in the surrounding environment. Vergence and accommodation are two major sources of depth information.

The visual system uses information from stimuli that are far away to gain information about other stimuli that are nearby. This is used to glean information about far-away objects like size, depth, or speed from the image/object that is nearby. Accommodation and vergence operate in tandem to maintain perceptual constancy of speed, depth, and size of stimuli. Imagery from HWDs may cause vergence to drift toward dark vergence; in dim light or low-contrast conditions, displays may cause misperception of the size, depth, or speed of the HWD imagery. Sufficient HWD brightness and contrast are required to minimize vergence shifting to dark vergence and accommodation (see following paragraph for explanation) shifting to dark accommodation. Moreover, the depth of focus should be large enough that images appear sharp and in focus (Winterbottom et al., 2006b).

Accommodation can be directly and indirectly affected by physiological factors, physical components, and cognitive factors. The tendency for the eyes to return to a focus distance of typically 0.5 to 2 meters in environments devoid of visual stimuli (i.e., total darkness) is called Tonic Accommodation (TA; Edgar, 2007; Iavecchia et al., 1988; Norman & Ehrlich, 1986; Owens & Leibowitz, 1978, 1980; Patterson & Winterbottom, 2006; Weintraub & Ensing, 1992). Because of this, information displayed at a focal length between 0.5 and 2 meters may act as a strong stimulus for accommodation. An individual’s TA position may moderate shifts in accommodation and are dependent on that individual’s resting focus (Edgar, 2007; Iavecchia et al., 1988). This is the case even when using an enhanced display device like an HUD. In conditions wherein there are very few or no visual stimuli (such as darkness or clear skies), this effect is more pronounced. While many studies have found no correlation between this effect and accommodation, it may be an issue when using HUD combiners that can draw accommodation. Edgar (2007) suggests that the salience of an HUD combiner be reduced or HMDs be used instead.

Vergence is the change in binocular fixation to objects at different distances; the vergence angle between the lines of sight of each eye adjusts to maintain alignment of the object image on the same area of each retina. Naturally, accommodation and vergence are coupled or linked together (Edgar, 2007; Rash et al., 1999). The decoupling or mismatch between accommodation and vergence can potentially cause eye strain (Ehrlich, 1997) or incorrect judgment of perceived distance, size, and velocity (Biberman & Alluisi, 1992; Edgar, 2007; Patterson & Winterbottom, 2007; Weintraub & Ensing, 1992).

Chromatic aberration is a failure to bring different wavelengths of light to a common focus. This failure forces re-accommodation of the eyes and subsequently causes visual fatigue (Weitzman, 1985). Past research has found that some cognitive and perceptual factors have an influence on the level of accommodation response. These are called closed-loop influences, where the accommodation can influence perception (accommodative response), and this can, in turn, influence accommodation (Wade, 1998).

Perceived distances (mental judgment of target distances) have been shown to affect the level of accommodation (Edgar, 2007; Jaschinski-Kruza, 1991; Rosenfield & Gilmartin, 1990; Westheimer, 1957). However, its specific effects are debatable, as some studies indicate the accommodative response tends to gravitate toward either the visual resting point (Malmstrom et al., 1980; Rosenfield & Ciuffreda, 1990) or to optical infinity (Kurger, 1980; Winn et al., 1991). Wick & Currie (1989) suggested the linkage between accommodation and vergence might drive the effect of perceived distances on accommodation.

Prior research indicates that vergence is a complex process that can respond to a variety of stimulations. Coubard (2013) summarized two prominent main stimulations for vergence: disparity and blur. When an object is presented to an observer, the retinas receive subtly different images between both eyes; thus, the single object is seen as two slightly different objects. This disparity is called diplopia. Thus, binocular movement (movement of both eyes to perceive the image) is required to accurately perceive an object. Landau (1990) divided disparity into two categories according to the disparity axis. Dipvergence is an attempt to cause both images in the eyes to be aligned at the same vertical angle. Convergence/divergence is a vergence movement that brings an object to the retinas with respect to horizontal disparity. Other factors that influence vergence are thinking nearness, change in size, or movement-derived cues (Coubard, 2013). It is important to clarify the effects of these cognitive factors on accommodation, vergence, and the interaction between accommodation and vergence.

The coupling between accommodation and vergence is a crucial function for distance, depth, and size determination and/or perception. However, HWDs decouple accommodation and vergence and present three-dimensional imagery in two-dimensional forms. This decoupling limits depth perception and may require the use of accommodation in order for users to perceive depth. When using an HWD, accommodation adjusts to the imagery presented via the HWD. If the user were to change their vergence, this may change the vergence angle with respect to accommodation and produce a mismatch (Robinett & Rolland, 1992). Due to the strong link between vergence and accommodation, any mismatch between them can create several issues for the user, such as eye strain, blurring of imagery, or visual discomfort.

HWDs are generally designed to present virtual imagery at or near optical infinity. The collimated image has been shown to maintain accommodation at or near the optical infinity (May & Wickens, 1995; Patterson & Winterbottom, 2006; Yeh et al., 1998), to eliminate eye-refocus time (Weintraub & Ensing, 1992), to improve visual scanning and detection (Fadden et al., 1998; Long, 1994; Wickens, 1997; Yeh et al., 1998), and to enhance navigation performance (Prinzel & Risser, 2004; Reising et al., 1995; Tsuda et al., 2011). However, some researchers have found that HWDs may not bring accommodation to or near optical infinity. The pilots do not perceive the virtual image as being in the same plane as the optical infinity (Biberman & Alluisi, 1992; Edgar et al., 1993; Weintraub & Ensing, 1992), causing reduced detection performance due in part to cognitive capture phenomena, where pilots focus attention on the synthetic display rather than OTW imagery (Prinzel & Risser, 2004). HUD research has illustrated how cognitive capture and attention tunneling can increase the chance that important but unexpected events occurring within a pilot's FOV (i.e., runway incursions) are missed (Haines, 1991; Wickens & Long, 1995; Wickens et al., 1998).

A number of researchers have suggested that the nature of experiment tasks, the relative image quality of the virtual image display and background, and attentional factors may influence the overall accommodation response in virtual image displays (Edgar, 2007).

Browne et al. (2009) varied the vergence of symbology in HWDs and found that an HWD reticle to a single viewing distance is not a good design solution. Moreover, a static vergence negatively affected performance on a targeting task. This experiment controlled for focus and allowed vergence to vary, creating a visual effect where an object at one depth could appear focused, and the same object at a different depth could appear blurred. This experiment showed that monocular viewing is uncomfortable for both near and farther target distances; it also produced the slowest response times (Browne et al., 2009).

Accommodation and vergence are known as strong cues for depth, size, distance, and velocity perception. Keller and Colucci (1998) suggested all four depth cues must be present for the realism of the virtual image. Whitestone and Robinette (2011) commented that HWDs provide a unique virtual imagery experience in operation, whereas the others do not. Reproducing these cues is a challenge for current HWD technologies, as virtual image displays tend to unnaturally decouple them. Additionally, at distances beyond 30 feet, accommodation and vergence do not contribute significantly to depth perception. For recommendations on values for supporting accommodation, refer to Table 5.

Table 5

Recommendations for Supporting Accommodation

Topic	Suggested/Recommended Value	HWD/HUD	Citation
Re-focusing time between near and far	70 milliseconds (ms) per diopter	HWD	Yeh et al., 1998
Accommodation and dark focus	Individual's dark focus accounted for 80% of the variability in the accommodative response in their experiments	HWD	Iavecchia et al., 1988
Luminance required for accommodative response	6.9 - 342.6 cd/m^2 (low to high)	HWD	Cupero et al., 2009
Low luminance	HWD focal distance tends to move farther from individual's dark focus (typically 1 m)	HWD	Patterson & Winterbottom, 2007
Accommodative response latency	370-1000 ms	HWD	Patterson et al., 2006
Time taken to re-accommodate from optical infinity to refocus on display < 31" away	2-3 sec	HMD	De Maio, 2000

Topic	Suggested/Recommended Value	HWD/HUD	Citation
Binocular overlap tolerance	A difference in luminance of no more than 30%, a horizontal difference of no more than 10 to 23 arcmin, a vertical difference of no more than 4 to 11.5 arcmin, a rotational difference of no more than 6 to 12 arcmin, horizontal or vertical differences in image size of no more than 1.5%, and a deviation between centers of the two displays of no more than 0.18 prism diopters	HWD	Patterson & Winterbottom, 2007
Binocular rivalry - eye dominance time	0 - 10 sec		Laramee & Ware, 2002
Boresight - for conformal symbol	< 1 milliradian (mrad)	HWD	Cupero et al., 2009
Boresight - for non-conformal symbol	<= 3 mrad	HWD	Cupero et al., 2009
Character space	50% of character height for grouped letters, 100% of character height for spaces	HUD	Weintraub & Ensing, 1992
Dark focus	Reduced by 1.95 log units under 34,262.6 cd/m^2	HWD	Patterson et al., 2006
Dark focus	Reduced by 4.2 log units under 3.4 cd/m^2	HWD	Patterson et al., 2006
Depth of focus	0.66 D (+/- 0.33) for target of size 1 arcmin (20/20 acuity) under 0.5 arcmin/4-ft-L (13.7054 cd/m^2)	HWD	Winterbottom et al., 2007
Dipvergence	3.42 to 84 arc		Landau, 1990
Disparity between 2 eyes in binocular	Head-up display specifications of 1 mrad or less difference between the right and left image channels for symbology within the binocular overlapped area if the symbology is seen by both eyes	HWD	Rash et al., 1996

Topic	Suggested/Recommended Value	HWD/HUD	Citation
Disparity between 2 eyes in binocular	When imagery is used with a minimum see-through requirement, the maximum displacement between the right and left image points within the bi-ocular/binocular region shall not exceed 3 mrad (0.3 prism diopter) for vertical, 1 mrad (0.1 prism diopter) for divergence, and 5 mrad (0.5 prism diopter) for convergence	HWD	Rash et al., 1996
Display lag - update and refresh rate	< 50 ms	HMD	Rash et al., 1996
Display resolution	20 lines per symbol height for non-alpha-numeric and moving symbols, otherwise 16	HUD	Weintraub & Ensing, 1992
Effect of pupil size on depth of field	1 millimeter (mm): 0.12 diopters - For each increase of 1 mm of pupil size, depth of field decreased by 0.12 diopters	HWD	Patterson et al., 2006
Effect of resolution on depth of field	1 step: 0.35 diopters - For each step of increase in resolution, depth of field decreased by 0.35 diopters	HWD	Patterson et al., 2006
Minimum exit pupil diameter	14 mm - should include the eye pupil (~ 3 mm), an allowance for eye movements that scan across the FOV (~ 5 mm), and an allowance for helmet slippage (± 3 mm)	HWD	Rash et al., 1996
Smallest allowable eye clearance for the standard eyewear	17 mm - 15 mm from the eye to the inner surface of the eye lens, and 2 mm glass thickness	HWD	Rolland & Hua, 2005
Recommended eye clearance	23 mm	HWD	Rolland & Hua, 2005
Inter-camera distance on binocular	240 mm yielded the most efficiency, 80 and 160 mm delivered double the estimated distance (experiment conditions are 80, 160, and 240; task was to estimate distance of an object at 300 m (participants did not know this distance))	HWD	Roumes et al., 1998

Topic	Suggested/Recommended Value	HWD/HUD	Citation
Average inter-ocular distance	63 mm	HWD	Stuart et al., 2009
Inter-ocular tolerance of luminance difference	< 30%	HWD	Patterson et al., 2006
Inter-pupil distance (IPD)	The range is roughly 53 to 73 mm, with the average range IPD being about 63 mm	HWD	Robinett & Rolland, 1992
Pupil size	15-17 mm is preferred for the design; 10 mm is acceptable	HWD	Rolland & Hua, 2005
Resolution	At an adaptation level of 100 fL, the eye can detect approximately 1.72 cycles per milliradian (cy/mr)	HWD	Rash et al., 1999
Resolution	Goal for HMD resolution in the central area of vision is 0.91 cy/mr, with values between 0.39 and 0.77 cy/mr being acceptable	HWD	Rash et al., 1999
Strong relationship between vergence and perceived size	0.61 or 0.95 m and 8 m	HWD	Patterson et al., 2006
Vertical viewing angle required to place HUD within their range as an attractor	20° - 25°	HUD	Martin-Emerson & Wickens, 1992

Dark Focus and Dark Vergence

Another visual perceptual factor to consider when using HWDs is the dark focus and dark vergence of the human observers. Dark focus, or TA, is the tendency of human visual accommodation to drift toward a resting focal distance, which is typically between 0.5 and 2 meters (Edgar, 2007). Patterson and Winterbottom (2007) found that in low illumination conditions, the eyes tend to automatically focus at around 1 meter for most people (dark focus distance). This is called the Mandelbaum Effect (Edgar, 2007). Dark vergence is the tendency for vergence to drift toward a resting distance (the resting state of visual accommodation). Dark vergence has been found to have an influence on vergence (Patterson & Winterbottom, 2006), as is the case where TA affects accommodation.

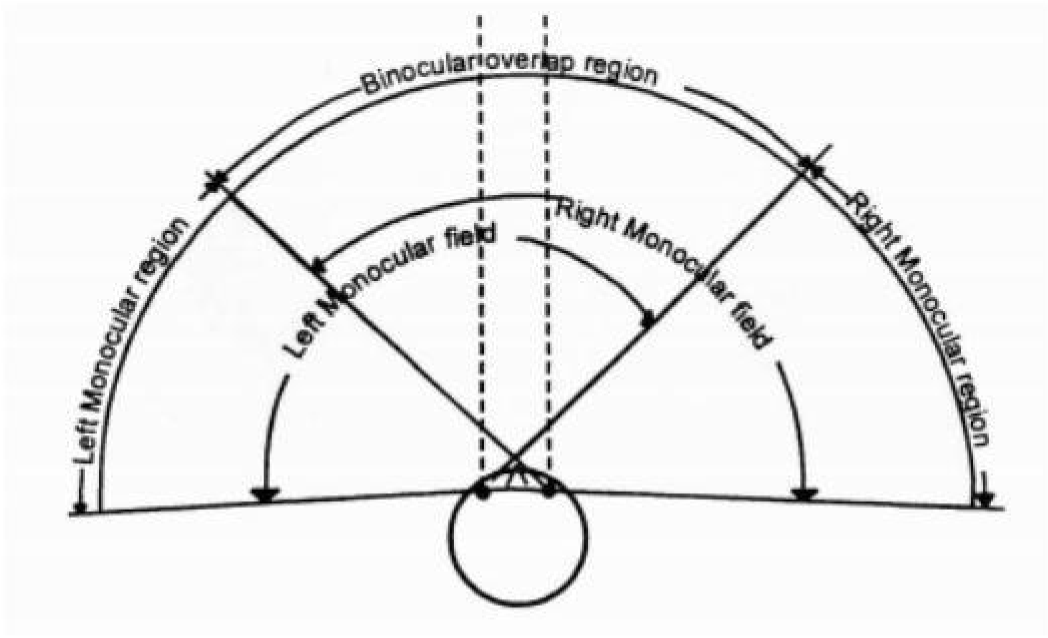
Similar to the depth of field, dark focus is dependent on the focal distance of the HWD. The focal distance of the HWDs may be located farther than the individual’s dark focus or dark vergence and may lead to misjudgments of the size, depth, or speed of presented imagery (Patterson & Winterbottom, 2007). Moreover, the focal distance for dark focus may vary between individuals. While viewing the OTW stimuli along with the stimuli from the HWD, there is a need for consideration of different focal distances since the images are superimposed. This means the OTW stimuli are always considered at optical infinity and the HWD presents symbology that is superimposed on the OTW stimuli. Since both the HWD symbology and OTW stimuli are collimated, the HWD symbology is perceived as being closer to the viewer than the OTW imagery (Edgar, 2007; Edgar et al., 1993; Patterson et al., 2006).

Field of View

FOV can be described as the extent of the observable world that can be seen by a human observer at any given moment. The extent of the FOV can be limited or expanded when using external visual devices, such as HWDs (binocular, monocular, and bi-ocular) and night-vision goggles. The range of available FOV depends on the design and construction of the external viewing device. Based on research conducted by Kasper et al. (1997), the FOV of an HWD depends on the design and resolution of the display. These factors impact the instantaneous FOV and the vertical and horizontal angular limits of vision at any given time. A limited FOV can degrade performance on spatial tasks such as navigation, object manipulation, spatial awareness, and visual search tasks (Baber, 2001). In addition, restrictions to a person's FOV can disrupt hand–eye coordination and affect their perception of size and space (Baber, 2001).

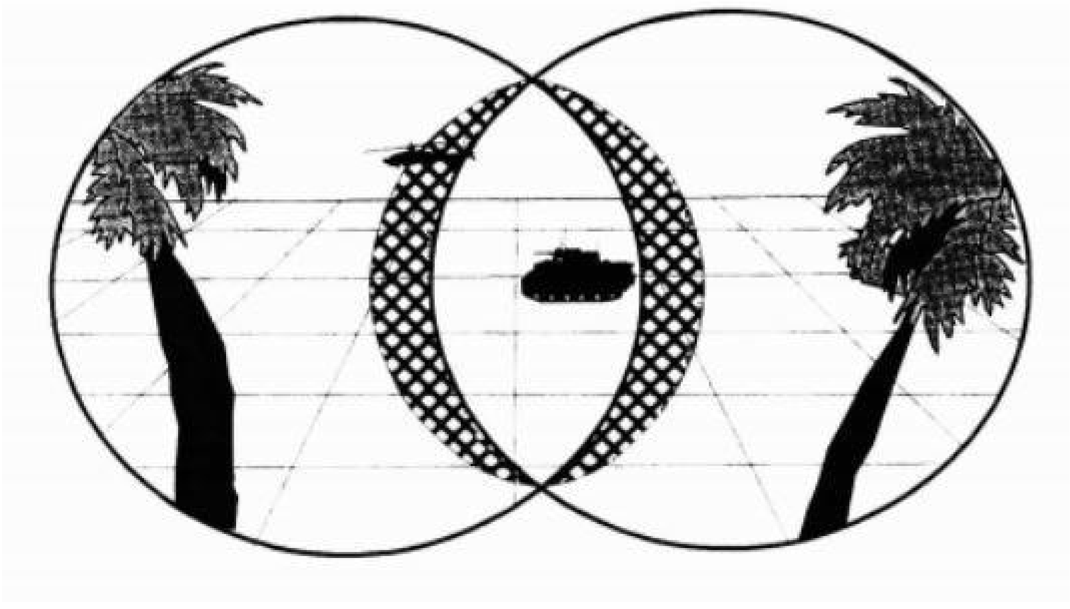
In binocular vision, the FOV of one eye overlaps with the FOV of the other eye. There are two general cases of overlap in the FOV in each eye: a full and a partial overlap. In the case of a full overlap, both eyes see the same image as if they were one eye; i.e., the FOV of images presented to both eyes consists of a single binocular region (Figure 6). In the case of a partial overlap, the FOV consists of a central binocular overlap region visible to both eyes and is flanked on either side by two monocular regions (each seen by one eye on either side; Figure 6 and Figure 7). This particular setup was designed to combat increases in the size and weight of HWDs associated with increasing FOVs (Klymenko et al., 2000).

Figure 6
Field of View Image Consisting of Overlapping Monocular and Binocular Regions



*(*Top View. In Normal, Unaided Vision, the Two Monocular Fields Are Partially Overlapped, Producing a Divergent FOV Consisting of Three Regions: the Central Binocular Overlap Region and Two Lateral Monocular Regions (Klymenko et al., 2000)*

Figure 7
Pilot's View of Visual World in an HWD with a Partially Overlapping Binocular FOV



In using a binocular HWD with partially overlapping FOV, each eye sees a circular monocular field against a black background. The real-world image of each eye matches in the binocular region, but in the monocular regions, this image is matched to the black background of the other eye, leading to visual effects such as binocular combination and binocular rivalry. A study on binocular overlap (Patterson & Winterbottom, 2007) found that a full binocular overlap showed better results than divergent or convergent overlap, in that both eyes in a bi-ocular system need to view the same image to mitigate rivalry.

Additionally, the user will see a temporally varying subjective darkening near binocular overlap borders, called Luning. This is the "subjective darkening of the monocular regions with the binocular region" (Patterson et al., 2007, p. 565). This effect is visualized in Figure 7 wherein the shaded regions on either side of the binocular overlap represent Luning. Moreover, it can cause fragmentation of the FOV into three phenomenally distinct regions and reduced target visibility in the monocular regions (Klymenko et al., 2000). A partial overlap of monocular image fields increased FOV and reduced the weight of the HWD without compromising much on resolution (Landau, 1990). It is possible to reduce the effects of this phenomenon with a "convergent display that has reduced luminance near the edges of the binocular region" (Patterson & Winterbottom, 2007, p. 566).

Studies have shown that pilots preferred increasing the FOV of their displays, as it helped reduce workload and enhanced control of the aircraft (Kasper et al., 1997). When the FOV was limited, pilots reported that more head movement was needed to accomplish the same tasks (Baber, 2001). This increase in head movement was associated with decreased performance. The pilots reported becoming more disoriented when moving their heads to overcome the restrictions of the FOV (Kasper et al., 1997). Moreover, increased head movements with a restricted FOV could result in fatigue, which would again negatively impact pilot performance (Kasper et al., 1997). A study on the impact of FOV on tracking tasks suggested increasing the FOV increases the speed of tracking targets and reacting to threats (Wells et al., 1989). However, if a target left the FOV, Wells et al. (1989) found no significant difference in the ability of subjects to recall the last position of the target, regardless of FOV size. Moreover, reducing overlap (smaller than 45 pixels vertical and 75 pixels horizontal) affects accuracy and reaction time (Landau, 1990). It is recommended the FOV on each eye for a seated user be roughly 140 degrees horizontally and 110 degrees vertically. The FOV for both eyes together should be about 195 degrees. For a moving wearer, a larger FOV is a necessary minimum of 60 degrees vertical and 75 degrees horizontal (Keller & Colucci, 1998). For recommendations on FOV, refer to Table 6.

Table 6
Recommendations for Field of View (FOV)

Attribute	Suggested/Recommended Value	HWD/ HUD	Source
FOV required to create a sense of immersion	> 50°	HWD	Patterson et al., 2006
FOV for full sense of immersion	Much greater than 60° would likely be needed	HWD	Patterson & Winterbottom, 2007
FOV required for flight simulation application	127°	HWD	Patterson et al., 2006
FOV provided by an HMD with two independent CRT displays	Two independent 60° fields for each eye with a 30° overlap can cover 120°-30° or 90° FOV	HMD	Biberman & Alluisi, 1992
FOV recommended	> 80°	HMD	de Vries & Padmos, 1998
FOV moving wearer or (assuming) moving vehicle	Min 60° vertical and 75° horizontal	HMD	Keller & Colucci, 1998
FOV	Breakdown at 45 pixels vertical and 75 pixels horizontal	HMD	Landau, 1990
FOV	200° horizontal, 130° vertical, and 120° of overlapping to simulate natural viewing (stereo)	HWD	Cupero et al., 2009
FOV	FOV as small as 40° may suffice	HWD	Cupero et al., 2009
FOV required for target recognition	Up to 127°	HWD	Cupero et al., 2009
FOV	20° for easy targets, 60° for harder targets	HWD	Wells et al., 1989
FOV	Seven combinations of FOV (40° circular to 60° x 75°), resolutions (20/20 to 20/70), and overlap percentages (50% to 100%) were studied, and the lowest and fastest terrain flights were achieved using the 40° - 20/60 - 100% and 40° - 20/40 - 100% conditions, with the aviators preferring the wider (60°) condition	HWD	Rash et al., 1999
FOV for flight tasks involving control of airspeed, altitude, and vertical speed	FOV of 50° (V) by 100° (H)	HWD	Rash et al., 1999

Attribute	Suggested/Recommended Value	HWD/ HUD	Source
FOV - 153°, 108°, and 45°	108° kept display efficiency at high levels	HWD	Eriksson, 2010
The binocular visual field where an object is visible to both eyes when the eyes converge symmetrically	About 114°	HWD	Rolland & Hua, 2005
FOV for successful performance, such as targeting and object recognition	40° may be sufficient	HWD	Patterson & Winterbottom, 2007
FOV on color perception - human limitation	Outside of 100° horizontal FOV, we do not perceive color	HWD	Arthur & Brooks, 2000
FOV on searching performance 48°, 112° and 176°	Searching performance degraded 12% on 112° horizontal FOV and 24% on 48° horizontal FOV (12% decrease for each 64° drop)	HWD	Arthur & Brooks, 2000

Ocularity: Monocular, Binocular, and Bi-Ocular

HWDs are designed in one of three major optical configurations: monocular, bi-ocular, and binocular. Their descriptions are repeated here for convenience. Monocular systems display one image to be viewed by a single eye. Both bi-ocular and binocular systems present imagery to both eyes; however, bi-ocular HWDs present a single image duplicated to each eye, while binocular HWDs present two non-identical images to either eye (i.e., Rash et al., 1998).

There are risks associated with some configurations, such as in monocular systems, namely binocular suppression or binocular rivalry. This phenomenon occurs when incompatible information is presented at the same retinal location to both eyes. The brain reacts in order to eliminate double vision by ignoring all or part of the image in one of the eyes (Baber, 2001; Cakmakci & Rolland, 2006; Cupero et al., 2009; Hubel, 2014; Laramee & Ware, 2002; Rash et al., 1998; Winterbottom et al., 2006b). With open HWDs, there is evidence the fusion of the OTW scene mitigates some of the effects of binocular suppression but does not eliminate it completely (Winterbottom et al., 2006b). However, this effect varies depending on whether the HWD is used for simulator flying or actual flying (Winterbottom et al., 2006b). If the conditions are met that do not promote binocular fusion, the user may experience discomfort, and the viewing of the HWD may be disrupted. Finally, binocular rivalry suppression affects the visibility of HWD symbology when monocular HWDs are used for augmented-reality applications. The suppressive effect on HWD symbology may be small for high-contrast symbology (Winterbottom et al., 2006).

Bi-ocular systems utilize a single video channel to both eyes, stimulating both eyes and, therefore, eliminating the ocular-motor instability of a monocular display. Binocular displays feature two independent video sources. They provide partial binocular overlap to increase the horizontal FOV without a drop in resolution, which is done by canting the video channels inward or outward.

In binocular and bi-ocular systems, it is crucial to align images/symbols displayed to either eye, although it may not be possible to align them perfectly. According to Landau (1990), a "mild" misalignment is acceptable because human eyes are capable of adjusting to some level of misalignment. However, even small errors in alignment can lead to increased head movements and a tendency for binocular rivalry. A greater degree of binocular misalignment can result in eyestrain, headaches, blurring, and double vision (Landau, 1990).

As with bi-ocular systems, binocular systems have their own associated advantages and disadvantages. The main problems with binocular configurations tend to be related to depth perception (Lippert, 1990). Usually, only one of several types of naturalistic depth cues—binocular disparity—is used to convey depth in these systems. Lippert (1990) additionally noted that the range of acceptable degrees of divergence between the imagery presented to each eye diminishes in just short periods of exposure to the imagery and continues to diminish when long-term tasks are facilitated by binocular systems. Binocular systems can provide the partial binocular overlap needed for the human visual system. In a study of the brightness of symbology or imagery presented in a binocular display, Lippert (1990) found the brightness imbalance tolerance for binocular HWD luminance is about 15%. Browne et al. (2010) showed that using a binocular HMD facilitated a shorter response time. Binocular systems produce a greater overall increase in duration threshold (duration of exposure to presented stimulus) and a marked increase in response and reaction time in binocular viewing conditions than the fused display condition of the monocular system (Winterbottom et al., 2007).

Another concern that needs to be accounted for is diplopia (double vision), which occurs often when pilots look at multiple objects located at different viewing distances. When directing attention to a given object, humans subconsciously suppress double vision of objects at other distances (Browne et al., 2009). Diplopia can cause floating, buried, or confusing symbology, double symbology, or the background imagery/symbology to be slanted, as well as general viewing discomfort.

A monocular system is, by definition, a single video display, which may cause issues with binocular rivalry and ocular-motor instability (Melzer, 2001). In some monocular devices, the asymmetric design can throw off the center of gravity of the head, which can be uncomfortable, can induce fatigue in the neck and shoulder muscles, and, in rare conditions, could cause spinal damage (Melzer, 1997). Another disadvantage to the monocular system is that it may limit the FOV of the user, which can degrade performance on spatial tasks such as navigation, object manipulation, spatial awareness, and visual search tasks (Baber, 2001). Depth of focus is especially a problem with monocular systems, as true depth perception is known to require both eyes. A study by Winterbottom et al. (2007) investigated the focal distance that is most advantageous for monocular systems. They found the optimal focal distance for a monocular HWD was about halfway between the nearest and farthest distances viewed through a simulator. With the use of the correct focal distance, it is possible to use monocular HWDs without blurred imagery or visual discomfort (Winterbottom et al., 2007). This suggests a monocular system should not necessarily be ruled out if these adjustments are accounted for. However, using monocular HWDs when the depth of focus is not properly adjusted may result in the users experiencing headaches and other side effects.

Monocular and binocular configurations can introduce issues regarding differences in illumination and the light-adaptive processes of the eye (Wickens et al., 2004). If the degree of illumination presented to each eye differs, this can lead to differently adapted vision, which effectively limits the ability to see with unaided binocular vision. Additionally, with monocular displays, the engaged eye matters. The dominant eye adapts faster than the non-dominant eye to lower levels of illumination ("dark adaptation") (Lippert, 1990). Using monocular display systems enables the user to allow one eye to adapt to the dark and the other to view the display (Lippert, 1990). Because bi-ocular and binocular configurations can more readily control the relative illumination at both eyes, lighting issues will have a greater impact with monocular configurations, especially when monocular displays are used in dark or changing light conditions. Additionally, with monocular displays, individual eye dominance potentially has an effect on binocular rivalry (Patterson, 2012; Rash et al., 1998). This can lead to problems when attention-switching between each eye is frequently required in order to process separate visual data sources (Baber, 2001). In a study conducted by Browne et al. (2010), training improved performance with the monocular device by 15%, regardless of eye dominance.

Symbology

Symbology has been successfully used to convey information efficiently in data-rich environments similar to the environment in a cockpit for the last several decades (Boestad et al., 1998; Voulgaris et al., 1995). Cockpit displays often use various symbols to indicate the various attributes associated with the airplane and flight status. Early employment of HUDs in the cockpit identified the need for concise coded symbology to convey complex data in a limited display space. Due to hardware differences and technological advancements, HWDs are not as constrained in terms of display space, and extended space or wider fields of view can be achieved with head-tracking systems; however, it is still essential that the information can be processed with minimal demand on the pilots' limited attentional and perceptual resources. According to Coppenbarger (1994), well-designed symbology can simplify complex information and increase ease of comprehension of the information.

Perception and interpretation of symbology can be influenced by parameters such as size, luminance contrast, color, stability, position, and natural-mapping properties of symbology. A wider gap between displayed symbology can increase the need for head movements, thus increasing the performance cost in order to obtain information (Martin-Emerson & Wickens, 1992). Such increased head movements may produce an experience comparable to simulator sickness, wherein a mismatch of sensory inputs causes physical discomfort, nausea, etc. Since the advent of virtual reality (VR) devices, it has been observed that wearing such devices may cause an experience similar to simulator sickness (Kim et al., 2018). According to Kim et al. (2018), simulator sickness is an umbrella term that includes VR sickness.

The natural-mapping properties of symbology also affect the perception, interpretation, and performance of pilots. Natural-mapping properties are those that are in accordance with the expectations of the users. Unnatural mappings between symbology and the outside world require pilots to invest their attentional resources to perceive and interpret the meaning of displayed information. This can lead to spatial disorientation (Biberman & Alluisi, 1992) and decrements in flight performance (Craig et al., 1997). Newman and Greeley (1995) found that misleading (i.e., unnaturally mapped) symbology caused pilots to misinterpret the height of obstructions in the flight path.

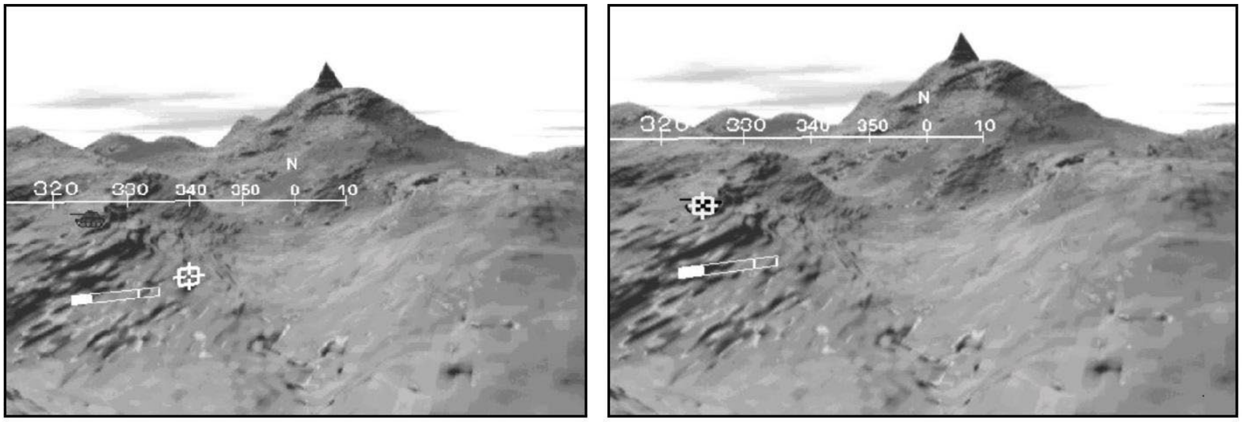
Another key issue in the interpretation of information in HWDs is symbol positioning and stabilization. Symbology positioning directly affects user information perception and interpretation. Kranz (1998) did a meta-analysis of major considerations for the evaluation of display symbology and reports using a Helmet-Mounted Cueing System (HMCS) and HUDs; the overlapping symbology not only affected its interpretation but also the perception of OTW scenery while burdening the pilot with attention transfer between HMCS symbology to HUD symbology and vice versa.

Conformal symbology spatially overlaps the OTW (or far domain) imagery (Wickens & Long, 1994) in a manner that tracks the OTW imagery and shows information about obstacles, flight paths, and threat areas with respect to the OTW environment. This information is displayed alongside relevant flight variables, such as attitude, horizon, flight path marker, etc. Conformal symbology has been shown to improve flight path tracking, event detection performance, targeting task performance, scanning performance, and response time (Fadden et al., 1998; Ververs & Wickens, 2000; Ververs, 1998; Wickens, 1997; Wilson et al., 2002).

Finally, the cues embedded in HWD imagery can be conformal or non-conformal, just like any of the other symbology. Yeh et al. (1998) conducted an experiment in which HWDs were used in a military targeting task. Conformal and non-conformal cues were used to guide attention, as shown in Figure 8. They found little effect of conformal-vs-non-conformal cues, but an interesting effect was found in targeting performance. Only in the cases where the events were expected did performance improve with an attention-directing cue. The guidance can have a detrimental effect in responding to unexpected events, and pilots' attention can be pulled to less relevant areas of the search task when cues are not understood upon their arrival.

Conformal symbology has been shown to inhibit the opto-kinetic reflex, which is responsible for simulator sickness (Iavecchia et al., 1988; Liggett, 2002).

Figure 8
Conformal and Non-Conformal Target Cueing



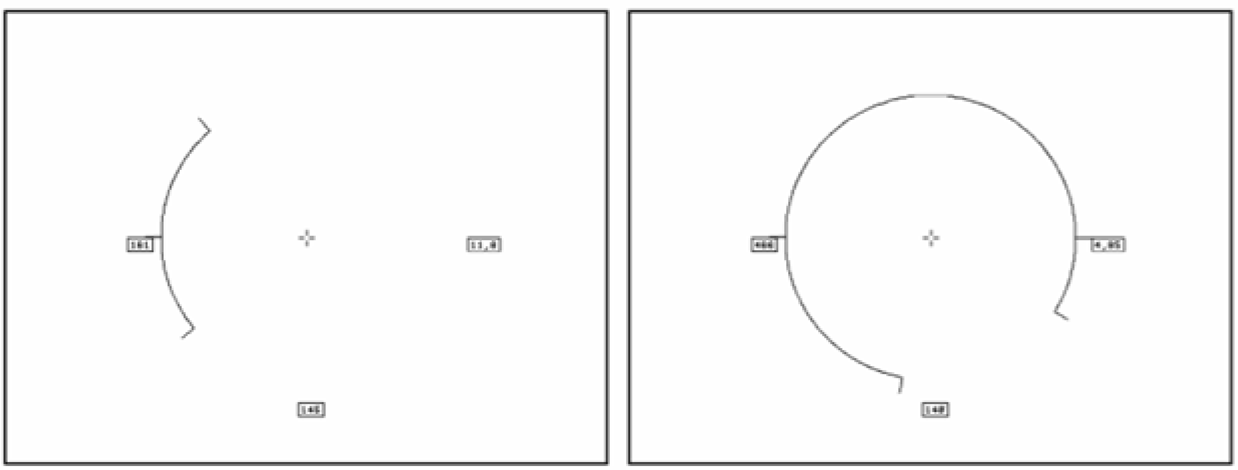
(a) (b)

*(a) Non-Conformal Target Cueing – Lock-On Information was Presented in the Same Location as the Cueing Arrow, Indicating that the Target was in the FOV of the Uuser. (b) Conformal Target Cueing – Lock-On Information was Displayed Over the Actual Object and Did Not Signal Presence of Any Uncued Targets that May Appear in the User's Forward FOV (Yeh et al., 1998). Appear in the User's Forward FOV (Yeh et al., 1998).

In addition to common aircraft flight variables, complementary technologies such as GPS and electronic moving map (EMM) can be integrated and present symbology in the HWD and can remarkably improve both safety and efficiency in the case of ground operations by improving on-ground navigation awareness and anticipating necessary control movements to navigate the path (McCann et al., 1998; Reising et al., 1995).

Various attempts have been made to develop standardized practical symbology on the flight deck. For attitude reference symbology, Self et al. (2002) designed arc-segmented attitude symbology, as shown in Figure 9, which improved pilot performance for both the outside-in display and the inside-out display.

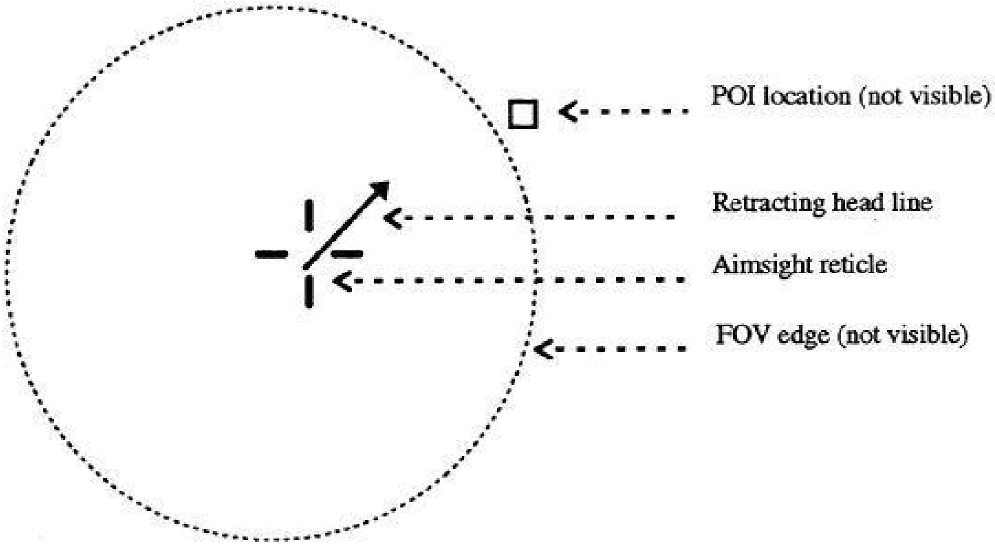
Figure 9
Arc-Segmented Attitude Symbology



*(Left: Attitude Arrow and Right: Circumferential Arrow; (Self et al., 2002)

Chandra and Weintraub (1993) found that the inclusion of an attitude "arrow" symbology yielded better recovery time in unusual attitude recovery tasks, and a circumferential arrow performed better than a straight-line arrow. Their results agree with Craig et al. (1997), who found that adding an arrow in the symbology yielded better performance in detection tasks; however, a retracting head line (as shown in Figure 10 below) showed the worst performance in total trial time, root-mean-square, closure rate, and subjective rating. One possible explanation of these results is that the arrow acts to guide the attention of pilots, thus imposing lower demands on attentional resources to search for areas/objects of interest. The poorer performance of the straight-line arrow and the retracting head arrow may be because of a lack of an "anchor" point, so discerning the directionality of the intended cue can take an additional mental operation.

Figure 10
The Retracting Head Line Symbology

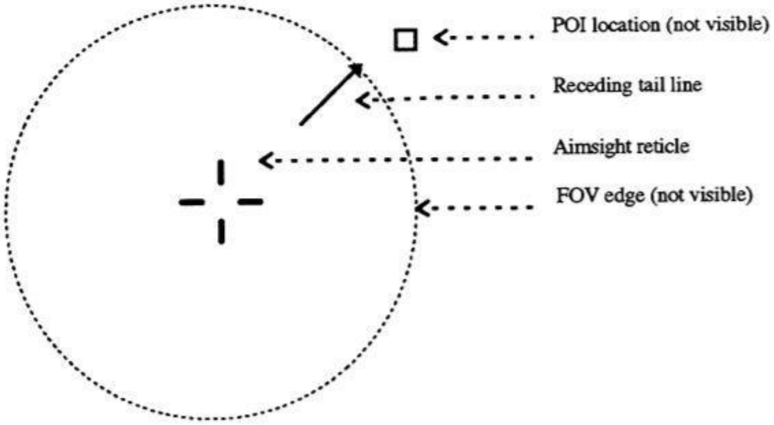


*Craig et al., 1997

Most HUD research concerning symbology is applicable to HWD applications. However, some symbology used in HWDs has been shown to worsen user performance compared to when they were displayed via HUDs (Coppenbarger, 1994), so it is difficult to draw conclusions across both types of advanced displays. More recent research has developed and shown success with HWD-specific symbology, which can better support tasks of maintaining flight attitude, especially for unusual attitude recovery (Weinstein et al., 1992; Wickens et al., 2007).

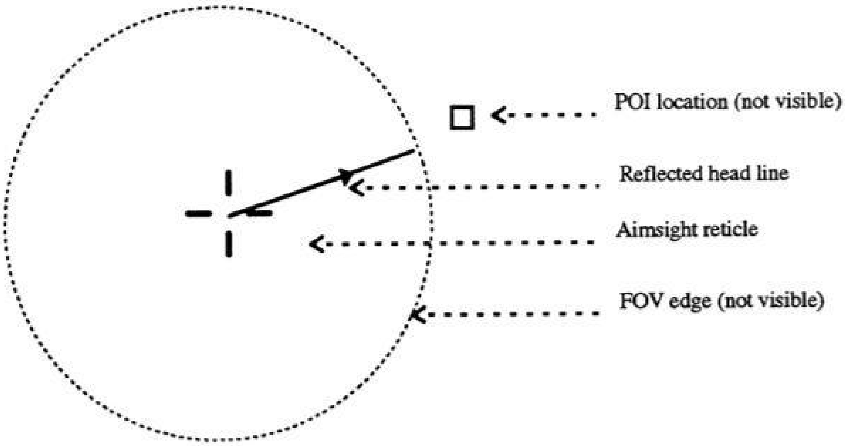
Craig et al. (1997) conducted an experiment to determine the impact of different types of “arrow” cues in an HWD-supported targeting task. Their results show target-detection performance was worse with the retracting head line arrow (see Figure 10 above) compared to other arrow types, such as the receding tail line (Figure 11) and the reflected head line (Figure 12), which supported equivalent targeting performance. The performance differences with the different types of arrow cues suggest some fundamental ways that attentional guidance can be more or less effective with well-designed cues.

Figure 11
The Receding Tail Line Symbology



*(Craig et al., 1997)

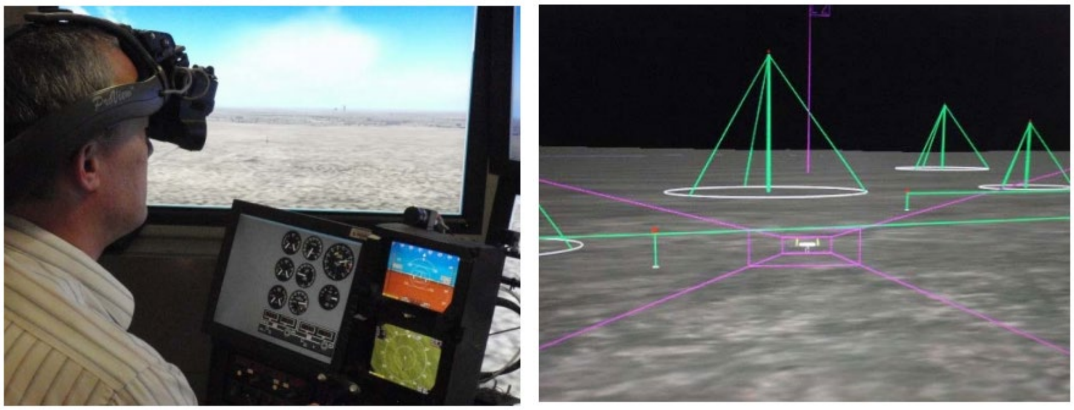
Figure 12
The Reflected Head Line Symbology



*(Craig et al., 1997)

A series of experiments (Beringer et al., 2009; Beringer & Drechsler, 2013a, 2013b; Beringer & Holcomb, 2010) using a Bell 206 helicopter studied the effects of providing information on obstacles via a Kaiser optical stereoscopic full-color see-through HMD in the flight path for rotorcraft pilots performing Helicopter Emergency Medical Service (HEMS)-type activity. They effectively used graphical overlays to convey the presence of/warn pilots about obstacles, such as power lines, in their flight path to prevent power-line strikes during descent. These graphical representations were presented as overlaid synthetic imagery using HMD. They were presented in six configurations of HMD obstruction image: low, medium, or high complexity paired with the ground plane symbol on or off (see Figure 13 for an example).

Figure 13
Experimental Set-Up and Screenshot of Obstacle Field



*(Experiment Set-Up (Left) and Screenshot of Obstacle Field (Right); Beringer et al., 2013)

One of these studies (Beringer et al., 2009) found that the use of HMD did not help with landing. They speculate this could be because the FOV was restricted vertically, and helicopter pilots usually looked outside to perform a landing.

They also found that highway-in-the-sky (HITS) guidance could help reduce travel time in that longer routes with fewer obstacles identified by the system took less travel time compared to shorter, more direct routes with obstacles (Beringer & Drechsler, 2013b). Additionally, Beringer and Holcomb (2010) found pilots often expected the representations of these obstacles to closely match reality.

Information Latency

One benefit of using HWDs is the reduced need for visual reorientations during visual scans that include environmental imagery (i.e., OTW) as well as head-up and HDDs (Biberman & Alluisi, 1992; Browne et al., 2009; Rash et al., 1998; Yeh et al. 2003). One of the ways this is supported in HWDs is via collimated imagery, which reduces the need to re-focus the visual plane of depth between optical infinity (OTW) and the symbology (Edgar, 2007). In order to support the binding of symbology and synthetic imagery to the relevant external environmental objects, sensor and computing technologies must seamlessly integrate the processing of the near-to-eye display, the head-tracking system, external imagery, and collimated symbology (Rash et al., 1998). Investigations of the time window of acceptability for synchronization of the related imaging have concluded display latency on the order of 50 milliseconds or less is preferred, 100 milliseconds is deemed acceptable, and anything near or greater than 150 milliseconds is unacceptable (Arthur et al., 2008). Head-tracking processing needs to be considered in this time window as well; greater tracking accuracy generally demands more processing time. Processing latencies in the HWD system can be quite problematic in supporting a stable visual experience (Arthur et al., 2008; Martinsen et al., 2003; Rash et al., 1998; Shelton et al., 2015). For head tracking, a boresighted (parallel aligned) solution within 5 mrad accuracy (the accuracy with which the head-tracking system updates the displayed imagery with the pilot’s head movements) must be maintained within the HWD eye box (the size of the cone of light when it strikes the retina) relative to the freedom of head movements (Curran, 2018). A misalignment feedback system should be developed to inform the user of any mismatch abnormalities (Bailey et al., 2011). Latencies can be present between control input and aircraft response, confounding any computational latencies of the HWD hardware.

Sensory conflict is one of the risks of using HWD systems with substantial processing latencies. The discrepancy between the actual sensory inputs (the actual OTW environment) and expected sensory inputs (an expectation of changes in the environment due to exogenous forces) can increase due to the distortion of visually perceived imagery (Rash et al., 1998). When multisensory inputs are in conflict, humans have an increased risk of motion sickness/simulator sickness, which is likely to affect flight performance safety (Arthur & Brooks, 2000; Biberman & Alluisi, 1992; Morphew et al., 2002; Rash et al., 1998).

Visual Clutter

Visual clutter is the term used to describe when data density is high, and the manner in which the data are represented imposes challenges to the user who is searching for key information. The user may have trouble parsing and distinguishing different types of information in a crowded display with complex image elements. One simple definition of clutter is “clutter exists when it is difficult to add a new salient item to a display” (Rosenholtz et al., 2005), in that a display is so crowded that it is hard to find space for an important, salient item in that display.

One problem with overly dense and cluttered visual displays is key visual data can be “masked”: covered up and/or indecipherable due to overlapping imagery (Kranz, 1998; Rash et al., 1998). HWDs showed better performance with target-related tasks than HDDs, especially when the targets were more salient, such as with an attention-guiding cue or a larger target. However, “clutter cost” can outweigh the performance enhancement of HWDs over HDDs if the targets are less salient (Yeh et al., 2003).

Transitioning from head-down panel displays to advanced visual displays such as HUDs and HWDs introduces new problems in visual processing due to clutter and obscuration. The OTW visibility gives essential visual cues to pilots; however, the virtual environment (VE) generated and presented via the HWD may not be an accurate representation of the OTW imagery (Foyle et al., 1995; Shelton et al., 2015). One advantage that HWDs have in this regard is a greatly expanded FOV facilitated by head tracking that supports multiple perspectives (Arthur & Brooks, 2000; Biberman & Alluisi, 1992; Osgood & Wells, 1991; Patterson & Winterbottom, 2006). Advanced techniques with HWDs can offer decluttering tools operated by a switch whereby the display will declutter based on switch position or integrated pilot programmable declutter modes (Kranz, 1998).

Another clutter-related challenge is that cluttered symbology has been found to inhibit and slow the detection of changes and important visual targets in low-visibility weather conditions (Arthur et al., 2014), low display luminance (Ververs & Wickens, 1996), and especially when events are unexpected (Fadden et al., 1998; Ververs & Wickens, 2000; Wickens, 1997; Wickens & Long, 1994, 1995). Jarmasz et al. (2005) explained that symbols that are isolated in spatially unique locations are attended to more often than grouped symbols. Therefore, conformal imagery, where one moving target is superimposed on a static target, is easier to attend to than nonconformal imagery. Because key visual data on overly dense and cluttered visual displays can be “masked” and/or indecipherable due to overlapping imagery (Kranz, 1998; Rash et al., 1998), removing unnecessary indicators from central visual areas or moving them to more peripheral visual locations can aid in reducing the negative effects of clutter (Zuschlag & Hayashi, 2003). Kranz (1998) suggested the need for advanced visual display systems to include a “declutter” function or mode and/or personal customized display layouts to reduce clutter costs. Such declutter modes have since been introduced in HUDs. Frey and Page (2001) found that simplistic displays that focus on communicating only the most essential data are best for approaches and landings. They also suggested hybrid systems in which the types of symbology and their orientation adapt during various flight contexts.

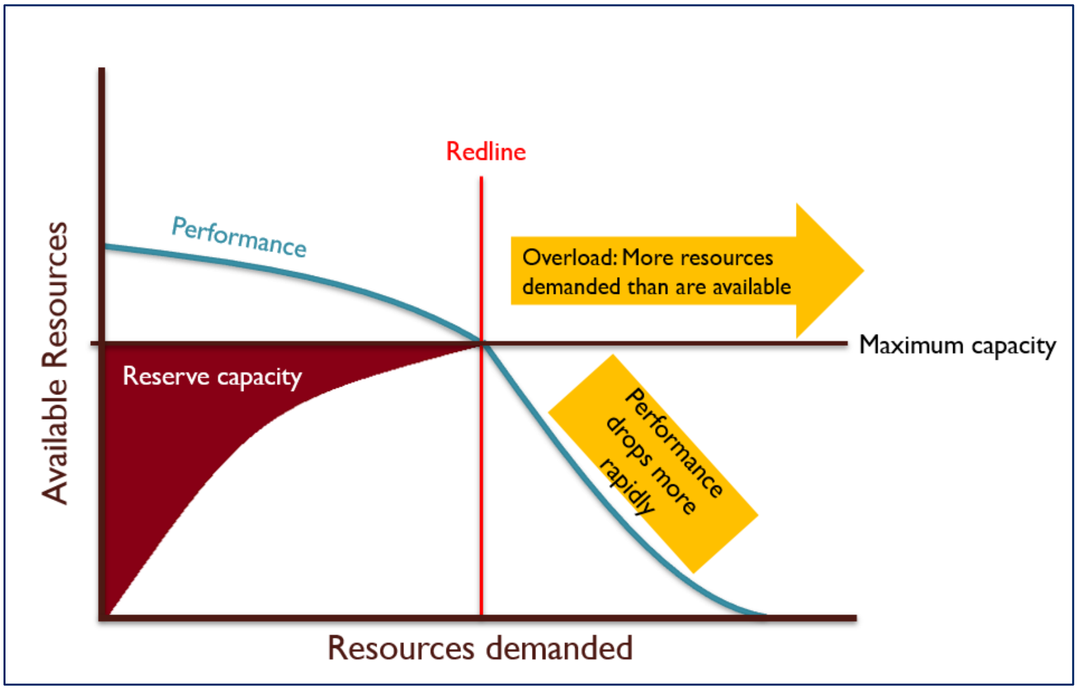
While a large amount of information can be represented on HWDs, humans have a limited capacity to process information; exceeding that limitation harms overall operational performance. Visual perception is hindered by dense and complex displays that include less relevant data that must be suppressed in order to locate and process more relevant visual data (Wickens et al., 2004a, 2012).

Workload and Performance

This section reviews human factors affecting the mental workload imposed by HWD usage and human task performance with HWDs. Mental workload refers to the demands imposed on the human user by the tasks they perform (Wickens, 2008). A pilot’s performance can be affected by the amount of workload imposed on them during flight. Counterintuitively, a pilot under exceptionally low workload may be susceptible to performance degradation (De Waard, 1996). The influence of HWDs on mental workload is a topic that has garnered attention going back several decades (Curry et al., 1979; Eggemeier & Wilson, 1991; Gopher & Donchin, 1986; Kramer et al., 1987; Lysaght et al., 1989).

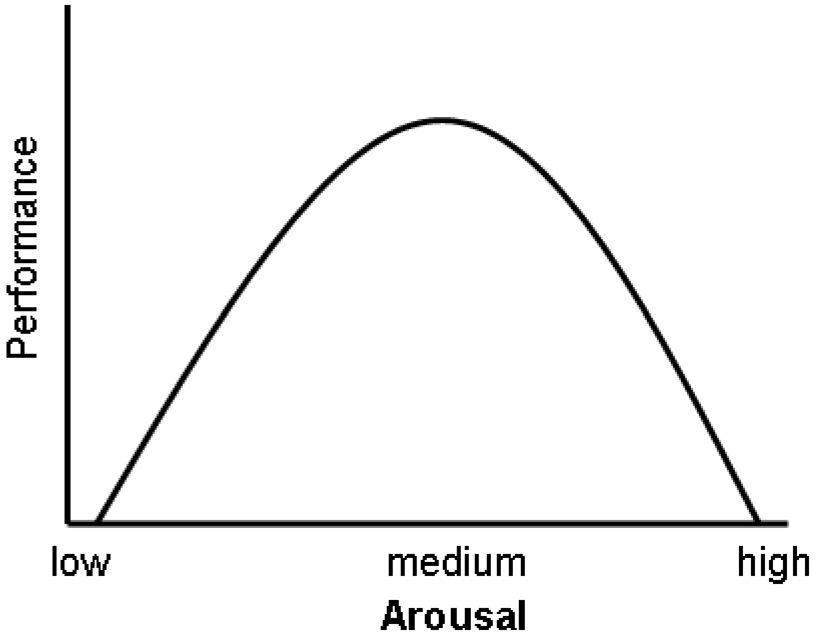
The difference between the demand for and availability of cognitive resources has an overall impact on performance. When the supply of cognitive resources equals demand, they reach a breakeven point and are said to have reached the cognitive “redline” (Figure 14; Wickens et al., 2012). If demand for cognitive resources continues to increase and the cognitive “redline” is surpassed, the individual’s overall performance will start to degrade (Grier et al., 2008; Wickens et al., 2012).

Figure 14
Difference Between Demand and Availability of Cognitive Resources



*(Adapted from Rodriguez et al., 2015 and Wickens et al., 2012)

Figure 15
Relationship between Arousal and Performance



*(Based on Yerkes & Dodson (1908), Hebb's Cue Function (1955), and Wickens et al., 2012)

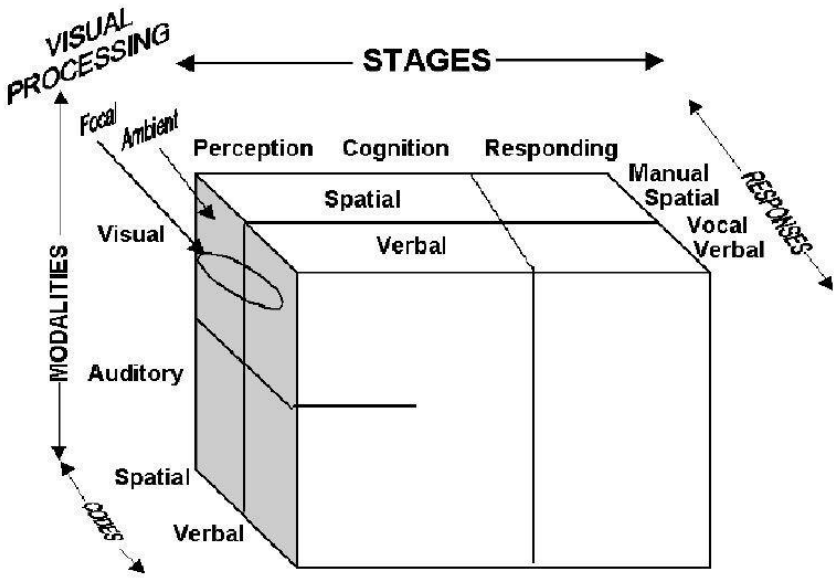
The relationship between arousal and performance can be depicted as an inverted U function, as shown in Figure 15. According to this, performance first increases with increasing arousal, reaches a maximum around a mid-level of arousal, and then falls as arousal further increases. This is often referred to as the Yerkes–Dodson curve (Yerkes & Dodson, 1908; Wickens et al., 2012).

De Waard (1996) divided this curve based on the amount of cognitive resources required to engage in a task. The leftmost region of the curve is a deactivated region where the tasks performed require minimal cognitive resources; in this case, the operator is underloaded. The middle region is the optimal performance region, where either the resource supply matches the resource demand or performance is not significantly affected, but the operator requires additional effort to maintain a constant level of performance. The rightmost region in the curve is when the operator may be able to perform the task even though they are overloaded. De Waard (1996) further posits a region with sustained low-level performance where the operator is overloaded when the resource demands already exceed the resource supply.

Human information processing theory and models, such as Kahneman's (1973) Capacity Theory and Wickens' (2008) Multiple Resource Theory (see Figure 16), can be consulted for design guidance in the selection and format of display media in HWDs and other advanced displays. If the perceptual and cognitive resources required of pilots in processing a display are insufficient or face significant demand from concurrent tasks, there may be a resource competition among these tasks, causing the overall performance to suffer (Wickens, 2008). For example, if a pilot needs to visually monitor the aircraft parameters displayed while concurrently piloting the aircraft, both tasks place heavy demands on the visual resources. Since the tasks draw from a common resource pool, the pilot may fail to detect a significant visual event, such as a precipitous drop in aircraft altitude.

Such resource competitions can be relieved and performance improved by engaging underutilized modalities in the performance of these tasks to distribute demand across available mental resources. For instance, if the aircraft monitoring task was an auditory task rather than visual (aircraft parameters are announced), the pilot can spare more visual resources for piloting the aircraft and use the available auditory resources for monitoring parameters.

Figure 16
The 4-D Multiple Resource Theory



*(For more information, see Wickens, 2008)

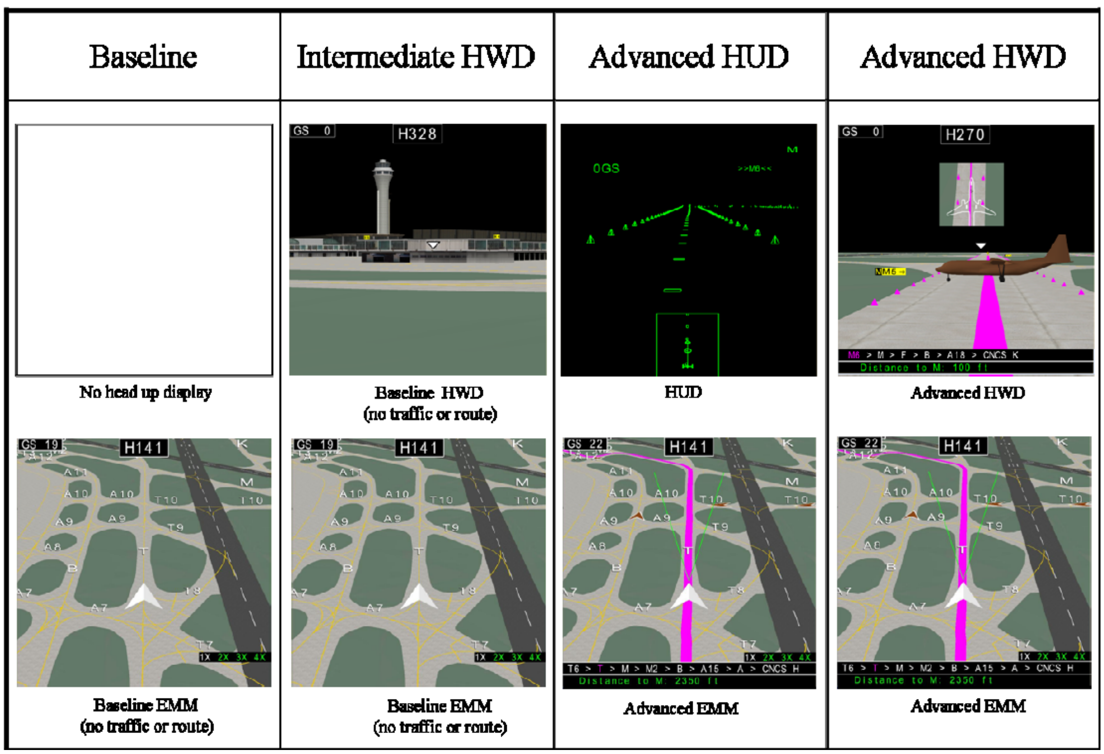
In a complex system, such as with a pilot in the cockpit, access to the right information at the right time is critical in maintaining the multitasking performance standard. Head-down instrument panels were found to hinder cognitive resource allocation as they require the pilot to switch his/her attention between optical infinity and the instrument panel (Weintraub & Ensing, 1992). The switching of attention comes with costs like increased head-down time, response time, and time taken to acknowledge a message communicated to the pilot (Biberman & Alluisi, 1992; Frey & Page, 2001; Weintraub & Ensing, 1992). It was also found that using HUDs could cause cognitive tunneling under overloaded cognitive states (Biberman & Alluisi, 1992).

Clutter can cause a “tunneling” effect with advanced displays such that the user focuses attentional resources to a greater extent on the display at the cost of sufficiently scanning their surroundings (Sanford et al., 1993). Cognitive tunneling is a state of cognition narrowing awareness or excluding information outside the highly attended regions (Thomas & Wickens, 2001). Cognitive tunneling can be a problematic issue because it can cause the change blindness phenomenon, which is an inability to detect an obvious change of stimulus (Simons & Levin, 1997). Detrimental attentional effects, such as inattentional blindness (failing to perceive salient stimuli in sight), can worsen with clutter (Dixon et al., 2013; Ververs & Wickens, 2000). Clutter distractions are much more prevalent and problematic in low visibility (Arthur et al., 2014). Additionally, Ververs (1998) found that conformal symbology did not improve performance during ground operation. Similarly, Sanford et al. (1993) found that conformal symbology induced cognitive tunneling rather than alleviating tunneling risks.

Martin-Emerson and Wickens (1997) suggested that conformal imagery promotes divided attention, which can lead to a reduction in the perceived depth difference between the optical infinity and virtual image display.

The National Aeronautics and Space Administration (NASA) conducted a series of studies evaluating the use of symbology for surface operations, takeoff, and landing using four different display conditions: 1. Baseline: Head-down EMM with no traffic or routing information; 2. Intermediate HWD: HWD with no traffic, routing, or clearance information; 3. Advanced HUD: HUD showing virtual airport but no traffic, routing, or clearance information; and 4. Advanced HWD: HWD with traffic and routing information (Figure 17) (Arthur et al., 2007; Arthur et al., 2008; Bailey et al., 2007). A full-color, monocular HWD was worn on the dominant eye, requiring glancing up to receive an uninterrupted stereoscopic view of the outside world. Two of these studies found no statistically significant difference in mental workload between navigation methods from subjective ratings collected using the National Aeronautics and Space Administration - Task Load Index (NASA-TLX) questionnaire (Arthur et al., 2008; Bailey et al., 2007). However, the other study (Arthur et al., 2007) using the same questionnaire had previously found the advanced HUD and advanced HWD both significantly reduced mental workload when compared with a head-down EMM by itself or combined with an HWD displaying the same information.

Figure 17
Displays Used to Test the Efficacy of HUDs, HWDs, and Their Symbology Across Three Studies



*(For more information, see Bailey et al., 2007; see also Arthur et al., 2007, 2008)

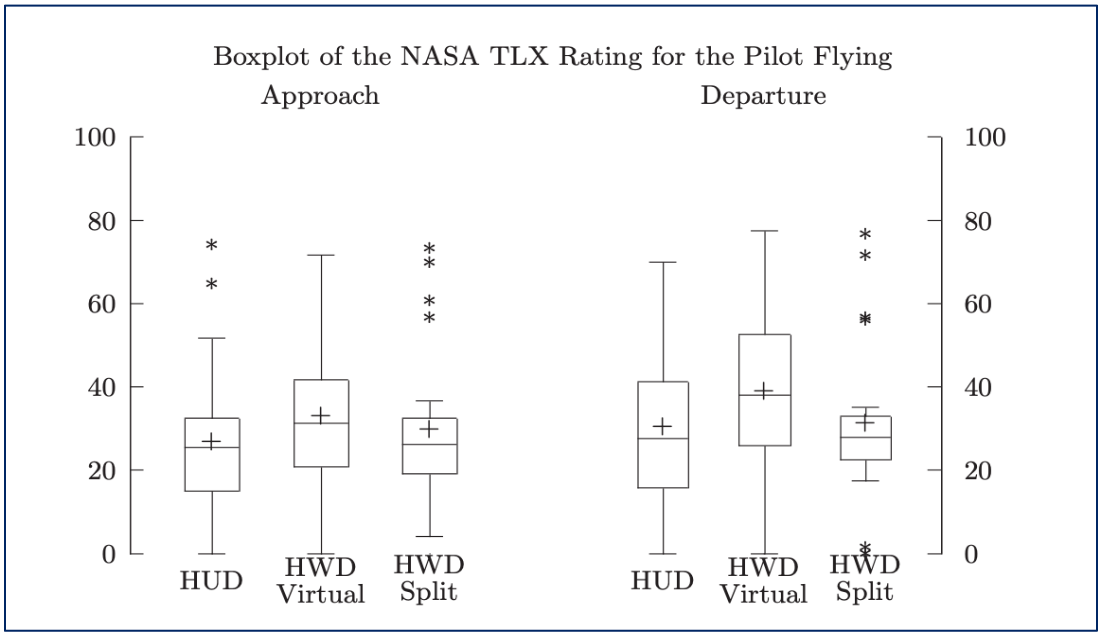
Investigating the approach task, Arthur et al. (2018) found no statistically significant difference in the mental workload between different HUD and HWD setups. Conversely, pilots using the Revised United States Air Force School of Aerospace Medicine (USAFSAM) workload scale have reported an increased mental workload when using an HWD compared with either a baseline instrument-only setup or an HUD; however, this was thought to be a result of latency and jitter issues with the particular HWD used in the study (Thomas, 2009). The Thomas (2009) study employed monochromatic green symbology displayed on the HUD and the bi-ocular HWD.

A study using the Revised USAF Workload Estimation Scale compared the effect of different HITS symbology in HUDs and HDDs on approach tasks and found no significant difference in workload between the different symbology or display methods except the baseline, no-tunnel displays imposed a higher workload (Prinzel et al., 2004). Further, a similar study using the Air Force Flight Test Center (AFFTC) Workload Estimate Tool found lower post-run mental workload when using a fused raster type and tunnel combination on the HUD compared to the baseline, no symbology condition (Prinzel et al., 2007). Helicopter pilots have reported a reduced mental workload associated with world-referenced conformal symbology when performing low-altitude spatial awareness tasks and contour flight tasks (Haworth & Seery, 1992). Pilots have reported a higher mental workload associated with command guidance symbology, which indicates how much control to input, compared with situation guidance, indicated surrounding obstacles, or a hybrid of the two (Wilson et al., 2002).

Mental workload was found to have effects on accommodative response. Edgar (2007) suggested that increasing workload is more likely to direct the pilot's attentional resources to the virtual display than toward optical infinity. With historical displays that are not collimated, this could result in problems when pilots need to divide attention to observe both OTW imagery and the HWD imagery, thus influencing accommodative response as well as mental workload. Contemporary HWDs/HMDs collimate visual displays at infinity to reduce this risk but still face attentional challenges due to the cognitive capture of salient synthetic display items (Haines, 1991; Wickens & Long, 1995; Wickens et al., 1998).

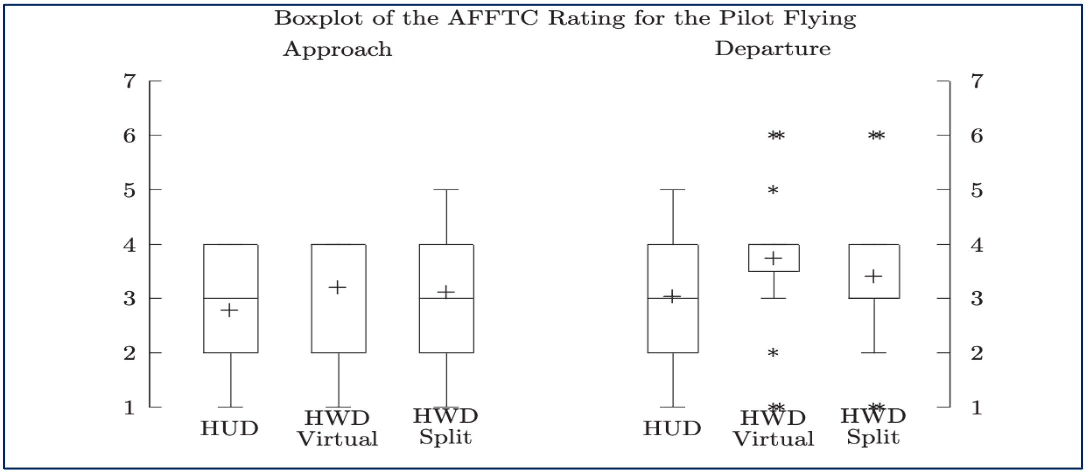
An experiment conducted by NASA compared workload induced by the use of an HUD to that induced by the use of an HWD with head tracking and found no significant differences between using an HUD or HWD based on the responses on the NASA-TLX (see Figure 18) and the AFFTC 7-point subjective workload scale (Figure 19; Arthur et al., 2014).

Figure 18
Box Plot for the NASA-TLX Ratings



*(For more information, see Arthur et al., 2014)

Figure 19
Box Plot for the AFFTC Ratings



*(For more information, see Arthur et al., 2014)

While the scope of this review focused on HWD issues relevant to civil aviation operations, the following table (Table 7) may be of interest and can additionally provide guidance for designers of aviation displays and Aircraft Certification specialists.

Table 7
Recommendations for Attentional Elements

Topic	Suggested/Recommended Value	HWD/ HUD	Citation
Attentional tunneling	Conformal symbolic visual cueing can lead to attentional tunneling, making important but unexpected events less likely to be detected. This tunneling effect is amplified in HWD compared to HDD and occurs even when the important events occur within 15° of visual angle from the cues.	HWD	Yeh et al., 2003
Delays	>=267 ms showed performance decrement	HMD	Rash et al., 1998
Detection	When catastrophic cueing occurred (location placed greater than 90° from the target), pilots performed 44% (47 sec) faster with HWD than with handheld display. Detection times: 101.4 sec for handheld display and 56.8 sec for the HMD	HWD vs. Handheld	Yeh et al., 2003
Maximum horizontal deviation between the centers of the displays or central corresponding points for imagery	0.50 diopter of base out prism or 0.18 diopter of base in prism	HWD	Rash et al., 1996
Stroke width for raster display/stroke written display	1:5 to 1:8 of symbol height/3- to 5-minute arc	HUD	Weintraub & Ensing, 1992
Symbol width	75% of height	HUD	Weintraub & Ensing, 1992
Symbology	Symbology size (height): 28-minute arc preferred for alphanumeric, 34-minute arc preferred for non-alphanumeric Symbology width: 75% of symbology height Stroke width for raster displays: 1:5 – 1:8 of symbology height Stroke width for written display: Line-width of 3- to 5-minute arc recommended Character space: 50% of character height of grouped letters and 100% of character height for spaces between words Matrix size: 9x11 is preferred, 7x9 is acceptable	HUD	Weintraub & Ensing, 1992
Presence of ghost horizon	About 11% better accuracy (initial stick input) compared to without ghost horizon	HUD	Weinstein et al., 1993
Symbology (conformal vs. non-conformal) on ground operation	Non-conformal symbology had 30% increase in taxi-path deviation compared to conformal	HUD	Wickens & Long, 1995

Topic	Suggested/Recommended Value	HWD/ HUD	Citation
Symbology (time full recovery)	Inside-Out symbology had 1.9 sec faster than ASAR symbology on time to full recovery	HUD	Wickens et al., 2007
Text frequency	< 10 Hz makes it difficult to read	HMD	Rash et al., 1998
Unexpected event detection	Unexpected events were detected in 50% of occurrences, while expected events were detected 95% of the time. Even when events are cued simultaneously and located within 15° of visual angle.	HWD	Yeh et al., 2003

Situation Awareness

Endsley (1995) describes SA as “the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future”. A high level of SA is critical for the safe and successful performance of the human–aircraft system. SA is critical to the successful operations of military aircraft and has long been a vital consideration for designing military and commercial aircraft displays and tools (Endsley, 1995). Endsley and Garland (2000) identified the loss of SA as one of the primary contributors to many human-error-related aviation accidents. Moreover, a major contributor to aircraft accidents is “Controlled Flight Into Terrain’ (CFIT)”, wherein an aircraft within the control of the crew is flown into terrain (or water) while the crew have no prior awareness (faulty SA) of the accident about to happen (Snow & Reising, 1999). It is also noted that general aviation (GA) pilots are more likely to be susceptible to the loss of SA due to possible lack of experience, including task management, basic procedures, vigilance, awareness of weather, troubleshooting malfunctioning systems, etc. (Endsley & Garland, 2000).

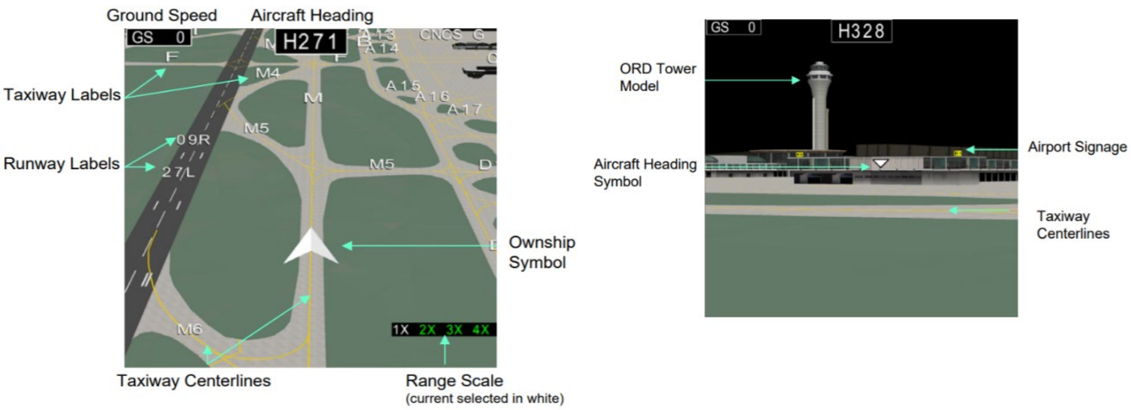
The safe operation of an aircraft depends on an accurate and complete assessment of the situation and the different parameters within and without the aircraft (Endsley, 1995). Terrain awareness is attained when the pilot is well informed about the position, altitude, terrain features, and hazards in the environment they are flying in. One way to attain and maintain SA would be to use informative displays, such as HWDs and HUDs, within an aircraft (Endsley & Garland, 2000).

One study showed that using HWDs can increase a pilot’s SA relative to using an HUD by increasing information processing efficiency (Geiselman & Osgood, 1994), and another, on military aircraft use, showed that HWDs have the potential to improve a pilot's situation awareness (Clark, 1995). A study that displayed synthetic terrain information on HUDs showed an improvement in the pilot’s terrain awareness (Snow & Reising, 1999).

Another study used a monocular HWD placed over the dominant eye of the user and compared the use of a basic HDD and an HUD and HWD, with and without traffic and routing information (Bailey et al., 2007). They used Situation Awareness Rating Technique (SART) to evaluate the SA of the user, and they found there was no statistical difference between the HUD and HWD. In a similar study using similar comparisons, Arthur et al. (2007) found that SA (measured using a post-trial subjective rating technique: the SART) was better when pilots used the advanced HUD and advanced HWD (with traffic and route information) compared to a baseline condition with another baseline EMM and the HWD without route information. However, there was no significant difference between the two advanced displays. Additionally, taxi SA questions were administered: a Likert-style post-run questionnaire for SA specific to taxi events, such as overall navigation, route awareness, traffic awareness, and taxi safety. They found no difference between the Advanced HWD and Advanced HUD. Another study comparing two HWD display concepts (HWD Virtual and HWD-split) and HUD found no significant differences in the SART rating for these displays (Arthur et al., 2018).

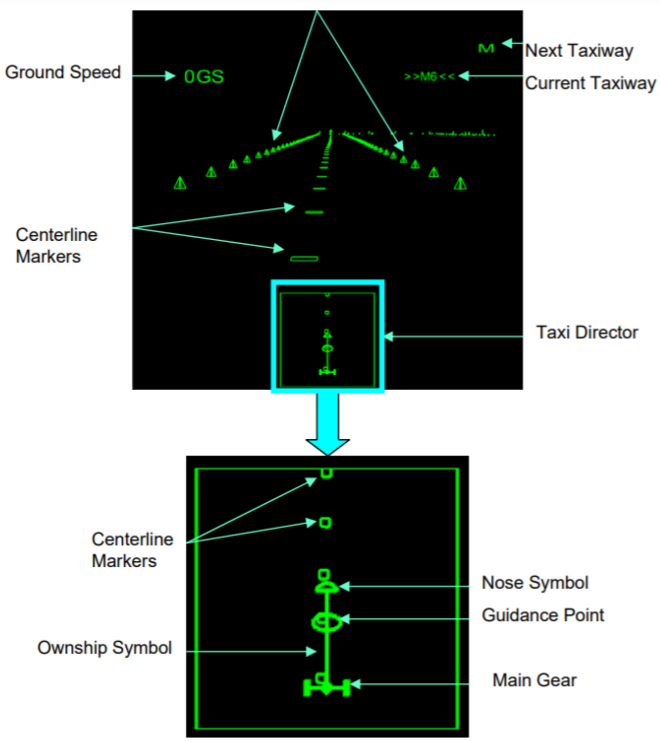
A study comparing three different hardware configurations, two different display modes (with or without head tracking), and either conformal or non-conformal FOVs (for the non-tracking mode only) found that while there was no significant difference between a baseline and intermediate HWD (Figure 20), the pilots did report higher SA with the intermediate HWD (Arthur et al., 2008). Subjectively, the test pilots reported greater SA when using any of the HWD concepts above compared to the EMM HDD or paper charts of the airport. They concluded that the advanced HUD (Figure 21) and advanced HWD (Figure 22) are comparable in both qualitative and quantitative results for SA.

Figure 20
Baseline EMM Display and the Intermediate HWD



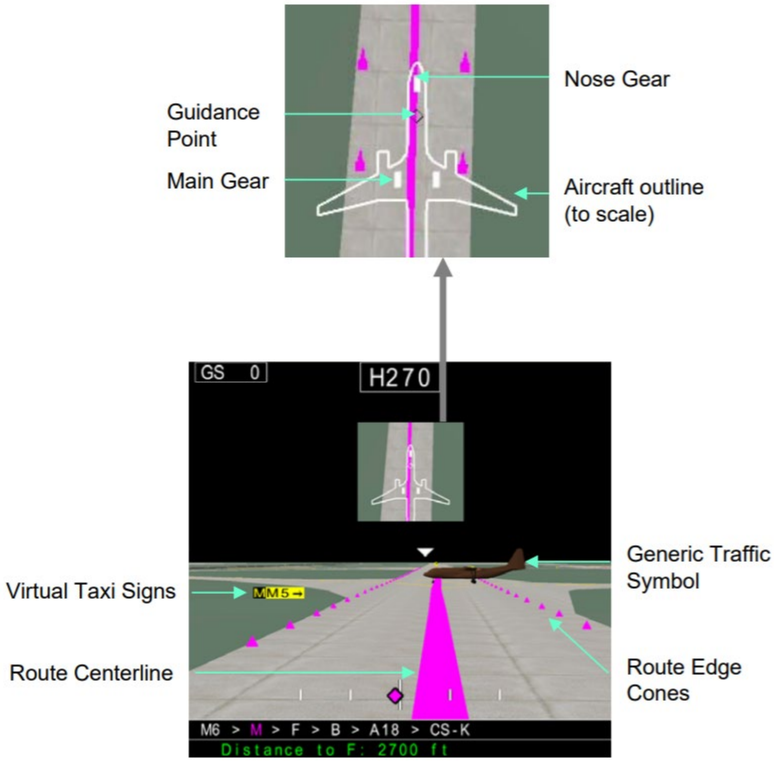
*(For more information, see Arthur et al., 2008)

Figure 21
Baseline Advanced HUD Use



*(Arthur et al., 2008)

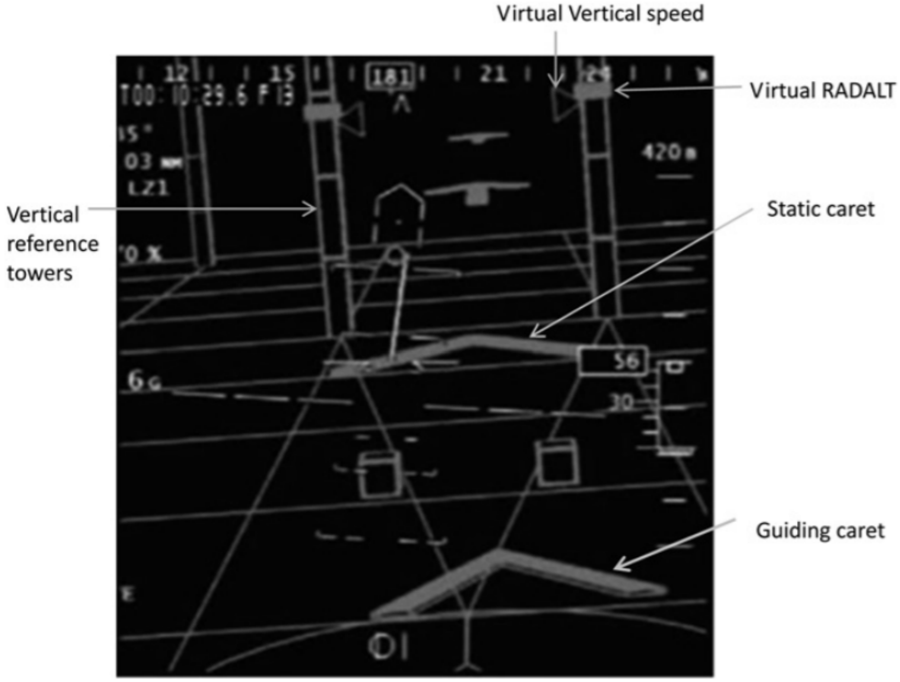
Figure 22
Baseline Advanced HWD Use



*(For more information, see Arthur et al., 2008)

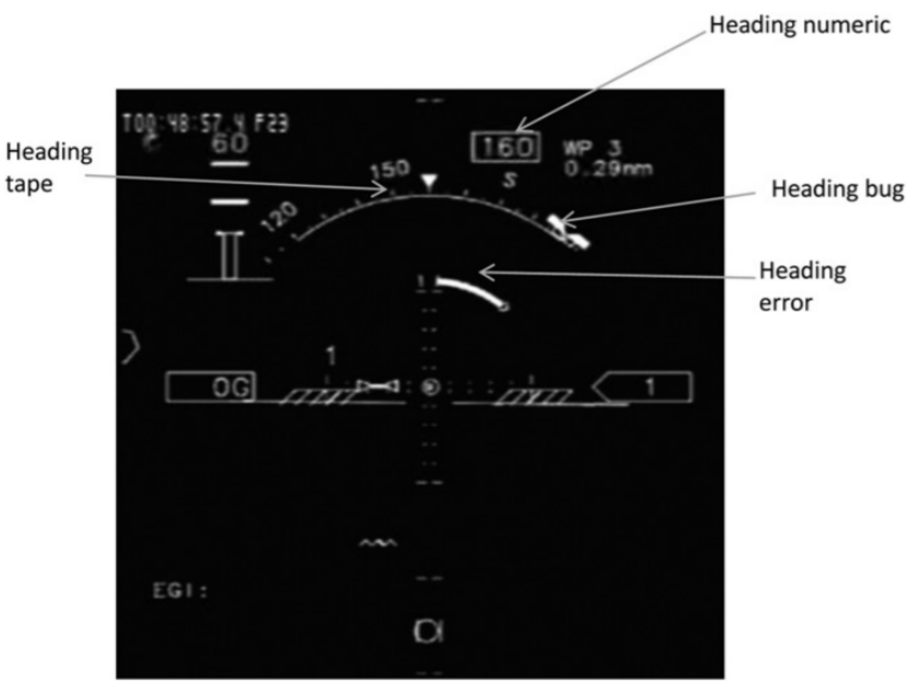
In another study comparing Helmet Display Tracking System (HDTS; Figure 23) and Brown Out Symbology System (BOSS; Figure 24) symbology for two-stage departure and single-stage approach in helicopters, it was found the HDTS symbology was better in that the pilots' SA showed a significant difference between the two types of symbology in both tasks (Cheung et al., 2015). Another study evaluated different HUD symbology and guidance concepts. Three tunnel concepts were compared: no tunnel, minimal tunnel, and a dynamic "crow's feet" tunnel. Further, two guidance concepts, a ghost-follow-me concept and a tadpole concept, were compared (Prinzel et al., 2004). In this study, they found the minimal tunnel was rated higher for SA when paired with the guidance concepts, and the highest SA was reported for the combination of the dynamic crow's feet with the ghost concepts.

Figure 23
Screenshot of HDTS 3D Conformal Symbology Use



*(For more information, see Cheung et al., 2015)

Figure 24
Screenshot Using BOSS Symbology *System* Use



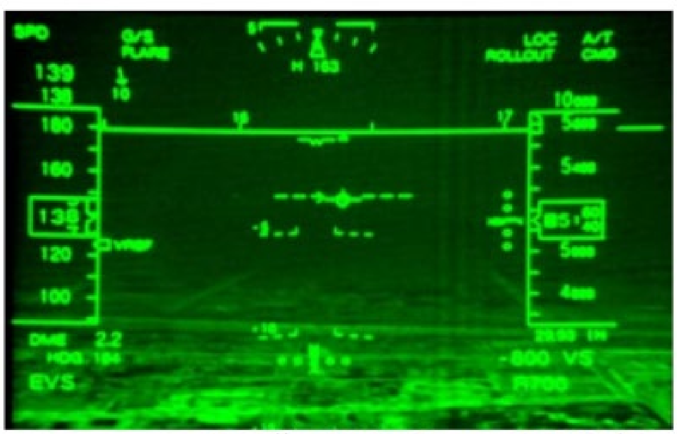
*(For more information, see Cheung et al., 2015)

Another experiment was conducted by NASA to evaluate whether pilot performance using an HWD with head tracking is similar to pilot performance using an HUD for certain flight tasks. This was done to justify the use of HWDs in aircraft where the installation of an HUD is impractical or impossible. For this experiment, the pilots and flight crews conducted approach and landing tasks as well as taxi and departure tasks. The pilot's situation awareness was evaluated using the 3-point SART after every flight trial. The results of the SART indicated no significant differences in how the pilots rated the SA provided by the HUD versus the HWD (Arthur et al., 2014).

In a different study testing HUD concepts of raster background, normal HUD symbology, and HUD symbology with pathway guidance, it was found that pilots reported greater SA, measured according to SART, with the raster-type HUD (see Figure 25; Prinzel et al., 2007).

Figure 25
Different HUD Concepts and Tunnel Use

Fused HUD Concept with Tunnel



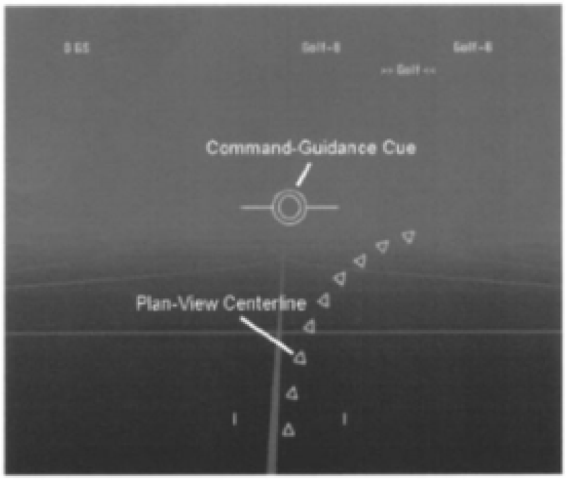
Baseline HUD Concept (EV Only) *(Prinzel et al., 2007)

A NASA study investigated pilots' taxi performance, situation awareness, and workload using three different types of HUD symbology: command-guidance, situation-guidance, and a hybrid of both. The command-guidance indicator specified how much control to input, the situation-guidance indicated surrounding obstacles, and the hybrid combined both types of symbology

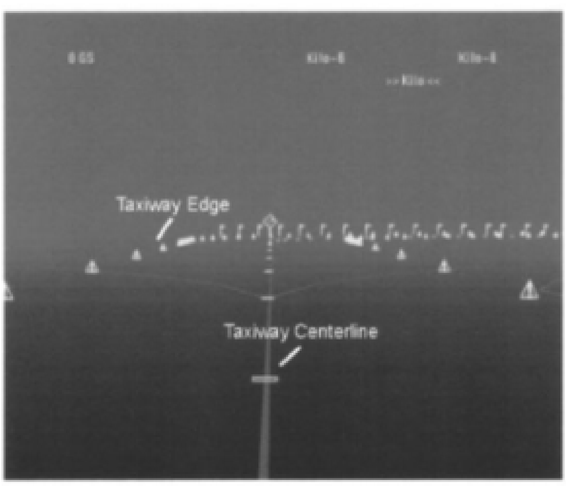
(Figure 26). When measuring SA on a Likert scale and using 3D SART, they found no significant differences between hybrid and situation-guidance symbology. Command-guidance required more time to look at and, therefore, had a lower SART rating (Wilson et al., 2002).

Figure 26

Command-Guidance and Situation-Guidance HUD Concepts



Command-guidance symbology overlaid on the forward scene (only center portion with HUD shown). Symbology shown is the command-guidance cue (labeled) depicting on-route tracking (i.e., concentric circles); the plan-view centerline (labeled) depicting an upcoming right turn, and lateral reference markers; ground speed indicator (upper left, showing 0 kts); and, text showing current and upcoming taxiways (upper right).



Situation-guidance symbology. Symbology shown is 3-dimensional taxiway edge cones (labeled) depicting an upcoming right turn; augmented taxiway centerline (labeled); ground speed indicator (upper left, showing 0 kts); and, text showing current and upcoming taxiways (upper right).

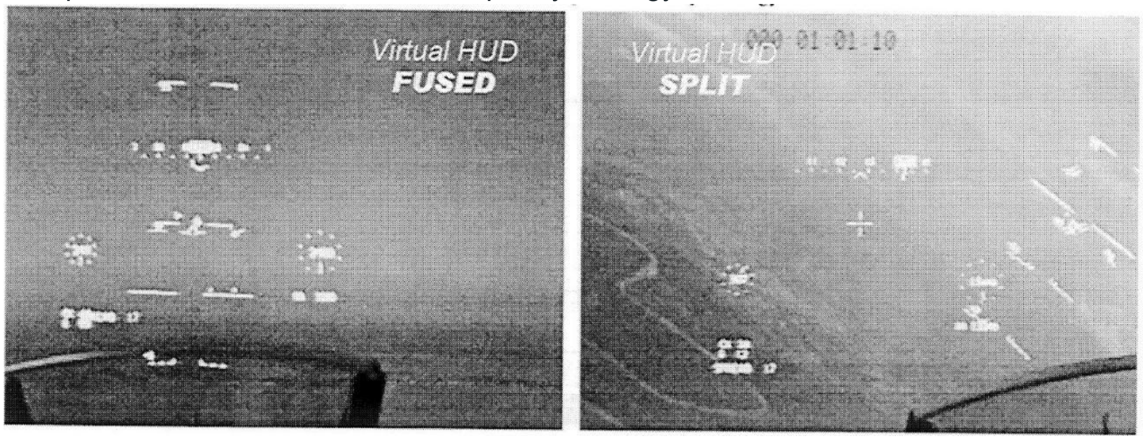
*(Wilson et al., 2002)

Attentional Cueing and Situation Awareness

The use of symbology in HWDs and HUDs was discussed in the context of means for information display in an earlier section of this report. In this section, the use of symbology is discussed in the context of information processing and cueing attention to support SA. Two different formats for displaying symbology in advanced displays, split symbology and focused symbology, are shown in Figure 27. While focused symbology has been found to cause excessive fixation upon the symbology, the heightened degree of focused attention may be beneficial in some tasks, such as takeoff and landing (Martin-Emerson & Wickens, 1992). The split display may be distracting to the pilot (Arthur et al., 2014).

Figure 27

Comparison between Focused and Split Symbology



*(For more information, see Frey & Page, 2001)

The salience of the symbology was found to be an important factor related to attention capture and guidance. Salience is the quality of a stimulus in standing out from all other stimuli in the surrounding environment (i.e., Yantis, 1993). Yeh et al. (2003) found that low salience targets are harder to spot with degraded cueing. They stated that low salience targets were a cause of cognitive tunneling. Echoing results from previous studies, the HWD was reported to produce tunnel-vision effects, during which a pilot felt their perceived FOV was smaller than the actual FOV (Foyle et al., 1995; Leger et al., 1999). This could result in a greater number of head movements and can be accompanied by the negative effects of a smaller FOV and an increased number of head movements. The color coding of the symbology was found to be useful as decluttering and attention guidance (Dudfield, 1991; Dudfield et al., 1995; Martinsen et al., 2002; Post et al., 1999).

The HWD symbology acts as a bridge between spatially accurate information and pilots' perceived information. The information displayed needs to be relevant to the tasks performed by the pilot since excessive information can cause clutter, leading to an increase in the detection time of both expected and unexpected changes. However, it is important to ensure that all relevant information is displayed so the pilot has sufficient information to make necessary decisions. Less than adequate information can hinder a pilot's ability for decision-making (Baber, 2001). Furthermore, HWD symbology should be designed such that it can support attention resource allocation strategies. The symbology should direct a pilot's attention to the appropriate place at the appropriate time. Introducing another modality, such as audition by using voice or sound prompts to cue the pilot's attention, has been shown to be a promising solution (Frey & Page, 2001; Bailey et al., 2007).

Additionally, one non-aviation study showed that the participants' performance was better when spatial information, rather than alphanumeric information, was presented in the HWD (Clark, 1995).

Physical Factors

The usage of HWDs in civil aviation cockpits introduces several relevant factors related to physical fatigue and performance. First, HWD usage implies more head movement and an increased weight imposed by any head-worn equipment. The Opto-Kinetic Cervical Reflex (OKCR) is the response that causes a pilot to subconsciously align their head with the horizon. Normally, pilots tilt their heads in the opposite direction of the aircraft rotation to stabilize the horizon. Liggett (2002) states that the OKCR occurs as long as the true horizon is perceived. The transition between frames of reference may be a cause for spatial disorientation. Liggett (2002) found that there was a statistically significant relation between head tilt angle and aircraft roll. Moreover, the head tilt effect was found to increase recognition time to airspeed and altitude information. It is suggested that an integration of frames of reference and appropriate symbology may be required in order to alleviate the disruptive transition. The transition between two frames of reference (an aircraft frame of reference and a world frame of reference) occurs when the true horizon is perceived while a pilot is flying an aircraft. A smooth transition between those two frames of reference can reduce OKCR. The attention guidance may be used to seize the pilot's attention on meaningful symbology to eliminate frame-to-frame transition (Liggett, 2002).

In an experiment concerning pilot head movement and HWDs conducted by Bailey et al. (2007), it was found that head movement occurred 97% of the time. The pilot's head was positioned within +/- 50 degrees in azimuth. However, azimuth data show that a longer tail could be interpreted as the need for off-boresight capability for commercial applications. The rate at which the pilot's head moved was recorded, and the data show that for the majority of the time, the pilot moved at a rate of +/-45 degrees per second. The experiment found that the maximum head-turning rates of 200 to 300 degrees/sec occurred. This is an important criterion to consider for the use of HWDs in civil aviation contexts, as head-tracking capability may be required in order to prevent motion sickness (Bailey et al., 2007).

Finally, head movements impact performance when wearing an HWD. Heavier HWDs can contribute to slower head movements. The time taken by the HMD to keep up with the head movements of the user needs some serious consideration. A larger lag between the head movement and the corresponding display update can cause greater discomfort to the user (Keller & Colucci, 1998). In one study using HWDs, the decrease in SA and increase in perceived workload when using the HWD was attributed to both the physical characteristics of the hardware and the noticeable head-tracking lag (Thomas, 2009). Head movement suppression may set an upper limit on allowable lag for display devices. A head-tracking sample rate of 120+Hz may be used to catch a majority of movements (Patterson et al., 2007). In a comparison between monocular and binocular systems, Melzer (1997) found that the monocular system was lighter, easier to manufacture and utilize, and inexpensive, whereas the binocular system was heavier, far more complex, and expensive.

Head Tracking and Cue Mismatch

Physical discomfort can arise for HWD users when mismatches are present between presented imagery and naturalistic cues. This discomfort can take the form of “simulator sickness” or spatial disorientation during HWD usage. These concerns often have detrimental effects on the physical functioning of the human body resulting from discomfort due to mismatches between presented imagery and naturalistic cues.

Additional physical elements of the HWD, such as strap tension, possible heat emission, and possible peripheral vision obstruction by the device, have implications for the user’s body; however, references to these elements were sparse, thus warranting further research on these topics. For recommendations on head-tracking and latency allowances, refer to Table 8.

Table 8

Recommendations for Head Tracking and Latency

Attribute	Suggested/Recommended Value	HWD/ HUD	Source
Head movement	180° for angular azimuth 130° for elevation 120° for roll (with an accuracy of about 1 - 2 milliradians (mrad) on boresight and about 2 - 6 mrad at a 10°eccentricity and linear displacements of 450 mm in the vertical axis, 400 mm in the horizontal axis, and 540 mm in the fore-aft axis)	HWD	Patterson et al., 2006
Head tracking recommended	< 30 mrad/sec for dynamic tracking accuracy	HWD	Rash et al., 1999
Head-tracking accuracy for boresight	2 mrad tolerance	HWD	Cupero et al., 2009
Head-tracking accuracy for off-boresight	Up to 10 mrad tolerance	HWD	Cupero et al., 2009
Head-tracking requirement	180° for angular azimuth, 130° for elevation, and 120° for roll, with an accuracy of about 1 to 2 mrad on boresight and about 2 to 6 mrad at a 10° eccentricity and linear displacements of 400 mm in the horizontal axis, 450 mm in the vertical axis, and 540 mm in the fore-aft axis.	HWD	Patterson & Winterbottom, 2007
Lag	Other cited studies recommend < 40 milliseconds (ms)	HMD	de Vries & Padmos, 1998
Latency - preferred	< 50 ms	HWD	King, 1995
Latency - preferred	< 40 ms	HWD	So & Griffin, 1995

Attribute	Suggested/Recommended Value	HWD/ HUD	Source
Latency - acceptable	40 - 300 ms	HWD	Rash et al., 1998
Latency - recommended	< 267 ms	HWD	Wildjunas, Baron, & Wiley, 1996 as cited in Rash et al., 1999
Latency - acceptable	267 ms	HWD	Wildjunas et al., 1996
Latency - preferred	50 ms	HWD	Arthur et al., 2014
Latency - acceptable	> 85 ms	HWD	Arthur et al., 2014
Latency - marginal	100 ms	HWD	Arthur et al., 2014
Latency - unacceptable	150 ms	HWD	Arthur et al., 2008
Latency	10 - 20 ms	HWD	Ellis et al., 2004
Latency	More than 67 ms time delay impacted performance.	HWD	Cupero et al., 2009
Latency	Decrements in pilot performance at 400 ms and 533 ms but not at 267 ms delays and below	HWD	Cupero et al., 2009
Latency	System lag as high as 146 ms had no negative effect on tracking task and workload.	HWD	Cupero et al., 2009
Latency	Adding 500 ms latency increased the estimation time by 30%	HWD	Grunwald & Kohn, 1994
Latency suggested for end-to-end requirement	< 20 ms	HUD	Arthur et al., 2015
Latency recommended for minimal effects to users	15 - 80 ms	HWD	Vincenzi et al., 2010
Latency beyond which perceptual problems occur, which leads to simulator sickness	> 80 ms	HWD	Vincenzi et al., 2010

Attribute	Suggested/Recommended Value	HWD/ HUD	Source
Latency maximum before performance degradation	> 80 ms	HWD	Rogers et al., 1997
Latency is not acceptable in HWD usage	> 300 ms	HWD	Rash et al., 2009
Latency as tested by So and Griffin, 1995	Tested 0, 40, 80, 120, and 160 ms latencies >=40 ms degraded performance	HMD	Rash et al., 1998
Latency	66.8 ms of delay was enough for performance decrement (tracking error) in both conditions	HWD	Nelson et al., 1995
Latency	Few performance decrements at 67, 133, or 267 ms; however, significant performance decrements were consistently observed in the 400 and 533 ms delay condition	HWD	Morphew et al., 2002
Latency on simulator sickness	With 119 ms delay, pilots reported no symptoms of simulator sickness, including nausea and disorientation	HWD	Morphew et al., 2002
Latency on simulator sickness	No appreciable increase in simulator sickness with increasing time delays above the nominal value of 48 ms	HWD	Morphew et al., 2002
Latency	Delays of up to 200 ms may be acceptable (90, 200, and 300 ms)	HWD	Morphew et al., 2002
Perception	1:1 scaling for symbology and OTW is recommended to immediately visualize the aircraft's trajectory (sometimes can be reduced to 1.5:1 or 2:1)	HUD	Haworth & Newman, 1993
Perception	Keep most of the data displayed within the central 15° FOV	HWD	Kranz, 1998
Perception	Object viewed near 0.61 or 0.95 and far (8 m) in real-image display	HWD	Patterson & Winterbottom, 2007
Perception (vibration)	At < 10 Hz, HWD has a legibility problem compared to HDD (at some frequencies below 10 Hz, HWD has legibility problem up to 10x compared to HDD)	HWD	Rash et al., 1999
Perception (distortion)	4% distortion is acceptable	HWD	Rash et al., 2009
Perception (distortion)	Bi-ocular/binocular region should not exceed 3 mr (0.3 prism diopter) for vertical (dipvergence), 1 mr (0.1 prism diopter) for	HWD	Rash et al., 2009

Attribute	Suggested/Recommended Value	HWD/ HUD	Source
	divergence, and 5 mr (0.5 prism diopter) for convergence		
Slew rate and acceleration for head-movement	300° per second - slew rate and 5000° per sec^2 acceleration	HMD	Rash et al., 1998
Detection	When catastrophic cueing occurred (location placed greater than 90° from the target), HWD performed 44% (47 sec less) faster than handheld display. Detection times were 101.4 sec for the handheld display and 56.8 sec for the HMD. HMD was faster than handheld by 44 sec.	HWD vs. HDD	Yeh et al., 2003

Simulator Sickness

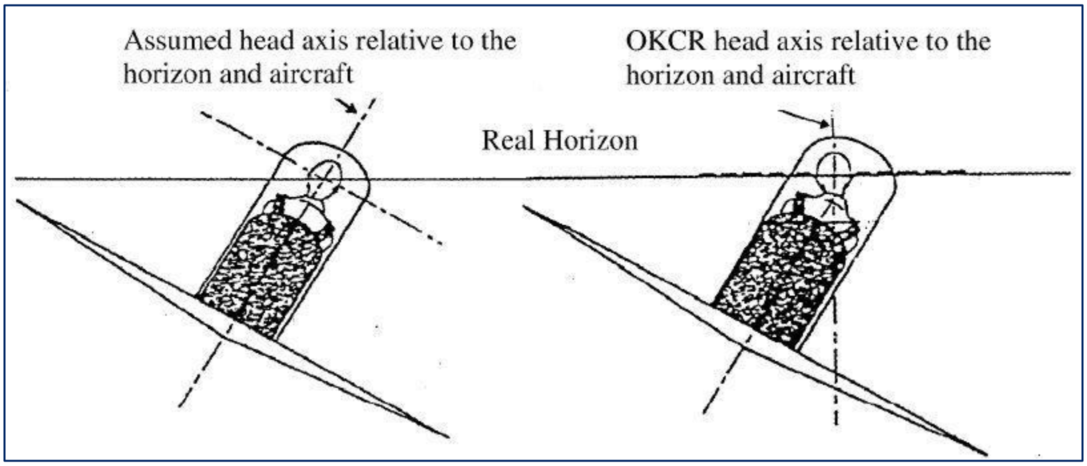
An HWD generates a VE, projects the VE onto its display, and reflects the visuals to be available to the user's eyes (Edgar, 2007) within their normal FOV. The HWD blends imagery from the virtual/simulated environment and multisensory cues from the natural external environment, and when there are mismatches in sensory input among the synthetic and naturalistic cues, it can result in "simulator sickness". Symptoms of simulator sickness are similar to those of motion sickness, including nausea, headache, disorientation, sweating, vomiting, fatigue, and eyestrain. These symptoms can be assessed according to their severity in three main subcategories: the nausea scale, the oculomotor discomfort scale, and the disorientation scale (Kennedy et al., 1993). Arthur and Brooks (2000) suggested that these three subcategories have different effects on VR compared to normal simulation. In VR, simulator sickness symptoms are disorientation, oculomotor, and nausea, respectively. However, in normal simulation, the symptoms are nausea, oculomotor, and disorientation, respectively. Thus, in VEs such as HWDs, disorientation may be a common symptom among users.

A comparison study evaluated four display types for use by pilots: EMM, Intermediate HUD, Advanced HUD, and Advanced HWD (with traffic and routing information; Figure 17). They used simulator sickness questionnaires to determine whether the pilots were experiencing any symptoms. In 11 of the 16 crews, there was no reported simulator sickness. When simulator sickness was reported, it was primarily due to oculomotor disturbances (Bailey et al., 2007). In the NASA study conducted by Arthur et al. (2014), simulator sickness was evaluated using 120 Simulator Sickness Questionnaires (SSQs) for 12 crews (10 per crew given at various times in the day). Only 5% of these SSQs showed any sign of simulation sickness, and all of these were reported as "slight symptoms."

Simulator sickness has been described as the outcome of either sensory and cue conflict/mismatch (Claremont, 1931; Oman, 1982; Reason, 1978) or physical postural stability (Riccio & Stoffregen, 1991). The sensory conflict theory describes simulator sickness as the result of receiving conflicting information from the different sensory channels with regard to movement and orientation (Claremont, 1931; Oman, 1982). Reason's (1978) neural mismatch hypothesis argues similarly that the conflict is in the mismatch between the expected sensory signal and the actual sensory signal, regardless of the engaged sensory channel. Oman's (1982) sensory–motor conflict theory explained that motion sickness is based on a mismatch between the efference copy of a sensorimotor signal and the actual sensations. The efference copy is the normally anticipated sensory input based on cues from exogenous forces and sensory rearrangements (Oman, 1982). Differences in the sensory signals between actual and efference copy sensations can lead to simulator sickness (Oman, 1982). Conflicting visual and vestibular cues can also contribute to the head-horizon tilt phenomena (Bailey et al., 2004; Patterson, 1995). The head-tilt effect has been shown to occur during in-flight visual maneuvers (Patterson, 1995). An example of the head-horizon tilt is the OKCR, which is an involuntary response where pilots tilt their heads while flying an aircraft, as shown in Figure 28 (Hasbrook & Rasmussen, 1973). The OKCR can contribute to cue conflict between the assumed and real orientations of the horizon (Liggett, 2002).

Figure 28

Head Orientations



*(For more information, see Hasbrook & Rasmussen, 1973)

A third theory used to describe simulator sickness stems from postural stability (Riccio & Stoffregen, 1991). The postural stability theory hypothesizes that motion sickness can result from instability in the control of body posture or the posture of segments. Postural stability can be described as "the state in which uncontrolled movements of the perception and action systems are minimized" (Riccio & Stoffreen, 1991, p. 202). Postural stability can continuously deteriorate over time or rapidly become unstable when performing various maneuvers, which means the severity of simulator sickness, as well as its onset over time, can vary broadly (Stoffregen et al., 2000).

Guignard and McCauley (1991) found that motion sickness was caused by motion in the 0.08-0.4 Hz range, which was later found to be only in the presence of low-amplitude imposed optical oscillation (Stoffregen & Smart, 1998). Stoffregen and Smart (1998) found that participants experienced postural instability before motion sickness occurred in fixed-base flight simulation, and the severity varied by personal vulnerability to motion sickness. Interestingly, they also found simulator sickness occurred more often when the visual system was engaged (Visual-Vestibular conflict; Hakkinen et al., 2002; Stoffregen & Smart, 1998). These findings agree with the cue conflict theory. Although the theory can predict simulator sickness by using a pilot's loss of postural control, it is still treated as a black box that has a nonlinear relationship, not only a single predictor or set of parameters of postural motion. In future research, a predictive simulator sickness model is required to be constructed in order to predict, prevent, and predetermine such a potential hazard of HWDs. However, the postural stability theory gives a solid explanation of involuntary stability and spatiotemporal perception, but it still fails to completely predict and explain simulator sickness due to a lack of supportive evidence.

The mathematical models of sensory conflicts proposed by Reason (1978) and Oman (1978, 1982) assume a linear relationship between the degree of conflict and the severity of the sickness. However, there is some evidence for nonlinear dynamics, considering that some symptoms exhibit different patterns, such as periodic waves of nausea at high severity levels and the decrement of nausea after emesis (vomiting) occurs (Oman, 1982). Additionally, these models may not be able to predict the adaptation process (how the human sensory system might adapt to conflicts) or other patterns in sickness that result from HWD usage. Past studies suggested that using HWDs unnaturally forces human visual perception processes to decouple accommodation and vergence and to use two-dimensional cues to determine depth in three-dimensional space (Biberman & Alluisi, 1992; Edgar et al., 1993; Ehrlich, 1997; Patterson & Winterbottom, 2006, 2007; Weintraub & Ensing, 1992). Additionally, optic oscillations (Stoffregen et al., 2000) and binocular movement (Hakkinen et al., 2002) can increase the prevalence of some symptoms.

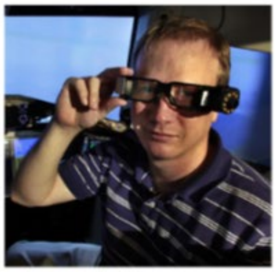
Understanding how HWDs can contribute to sensory/perceptual discrepancies among different modalities, such as the visual, auditory, tactile, and vestibular senses, is increasingly important, as HWD systems have increasing capabilities to present multisensory cues. It is important to observe the effects of simulator sickness on performance, both in simulated and real flight contexts that blend synthetic and natural cues.

Impact on Simulator Sickness

In a study that used straight-in runway approach tasks to evaluate HWD and HUD for use in EFVS operations (see Figure 29), the SSQ results were nearly equivalent for the use of both HUD and HWD (Arthur et al., 2018). However, the HUD users reported more nausea-related symptoms (general discomfort, burping, stomach awareness), and HWD had more oculomotor (eye strain, headache, fatigue, general discomfort) and disorientation symptoms (Arthur et al., 2018).

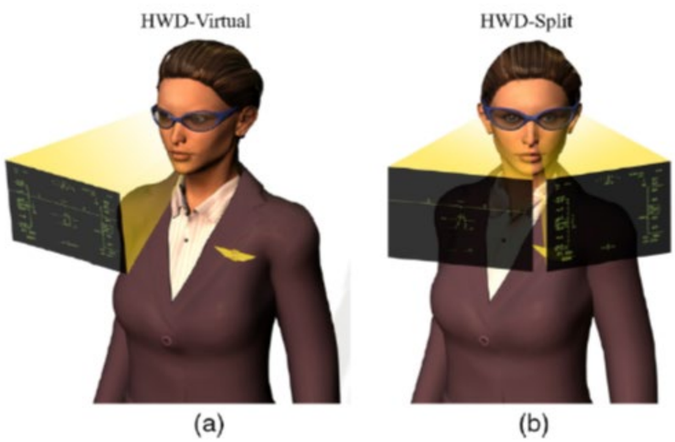
Figure 29

HWD, HUD Symbology and HWD Display Concepts Used in EFVS Operations



The HWD system used in the experiment.

The HUD system used in the experiment. The HUD symbology consisted of typical elements: airspeed and altitude tapes, pitch ladder, roll scale, flight path marker, mode annunciations, flare cue, and runway outline.



The two HWD display concepts used in the experiment. (a) The HWD-virtual displays a virtual HUD in the HWD, where the actual HUD symbology would appear (about 20 ft outside the window). (b) The HWD-split concept displays nonconformal symbology (tapes, roll scale, text) as screen-referenced elements, thus, these symbologies are always in view. Conformal elements (flight path marker, runway outline, watermark) remain referenced to the earth.

*For more information, see Arthur et al., (2018)

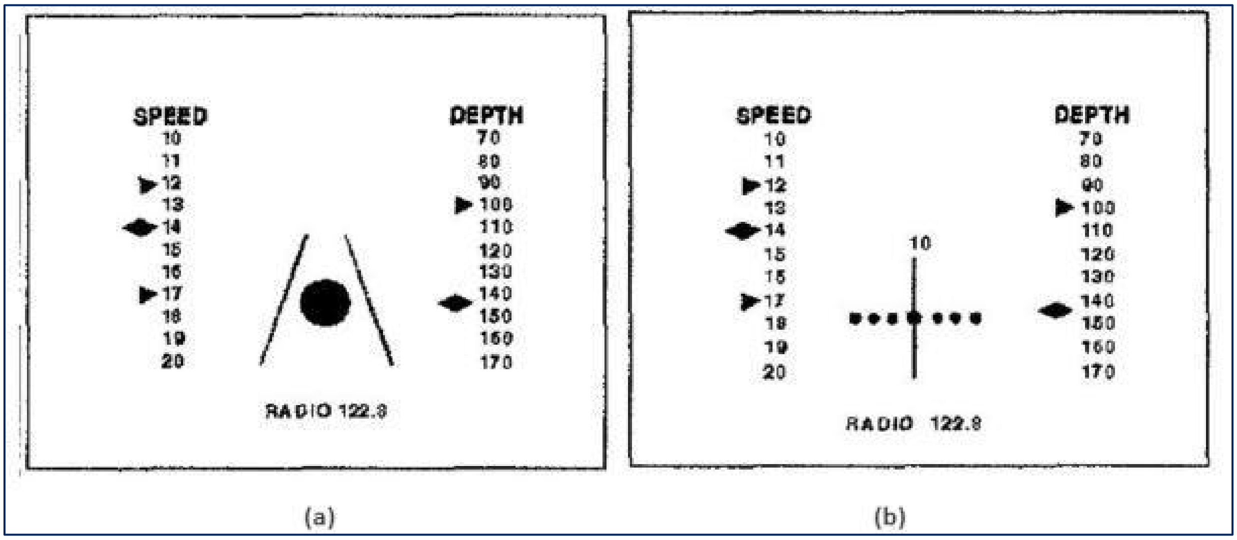
Spatial Disorientation

Spatial disorientation can be one consequence of the mismatch among perceptual cues, such as vision and vestibular senses (Biberman & Alluisi, 1992).

Past research has found pilots do not perceive virtual symbology to be at optical infinity (Biberman & Alluisi, 1992; Cupero et al., 2009; Edgar, 2007), but they perceive the symbology presented in the display and the OTW environment at different distances. It is possible to counter this by introducing visual aids within the cockpit that can serve as an additional frame of reference in the system. In doing so, pilots have two frames of reference: one inside the aircraft and the other outside (Liggett & Gallimore, 2001). This is useful when pilots require a transition between optical infinity and the HWD symbology in order to control the aircraft. A lack of transitioning smoothness between the two frames of reference can cause an inability to accurately interpret the actual position of the aircraft (Liggett, 2002; Liggett & Gallimore, 2001). The OKCR was found to be an unconscious reflex in order to match the earth frame of reference and the virtual frame of reference (Hasbrook & Rasmussen, 1973; Patterson, 1995). Binocular rivalry was found to interrupt a smooth transition between the two frames of reference by causing one information source to be dominant over the other. It was associated with decrements in spatial awareness, visual search task performance, navigation, and object manipulation (Baber, 2001; Browne et al., 2010; Cakmakci & Rolland, 2006; Frey & Page, 2001). Additionally, Bailey et al. (2004) found that large yaw head movements due to system latency increased disorientation and workload.

Conformality is considered to be a contributing factor for spatial orientation. Conformal displays have been shown to improve flight tracking and monitoring tasks (Figure 30; Brittisha & Curt, 1996; Long, 1994; Martin-Emerson & Wickens, 1997). Martin-Emerson and Wickens (1997) suggested that conformal displays may encourage parallel processing (when two or more stimuli are processed simultaneously).

Figure 30
Conformal Displays



*(a) Conformal Display – Course Depicted Using Two Lines with the Ship's Position Depicted as a Circle and (b) Non-Conformal Display – Course Depicted by a Needle and Course Deviations Conveyed via Dots (Brittisha & Curt, 1996).

Usability

Usability tests help researchers identify the best way to set up an experiment and can provide useful, subjective feedback on different equipment configurations without having to go through rigorous data collection and testing.

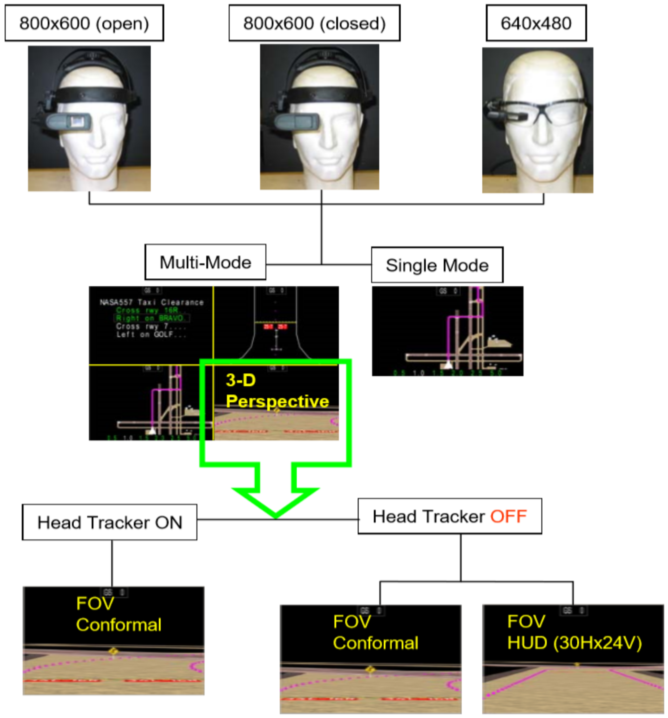
A comparison simulator study testing the efficacy of using HWD for taxi operations evaluated four display types for use by pilots: the baseline display, which is the EMM, Intermediate HUD, Advanced HUD, and Advanced HWD (with traffic and routing information) (Arthur et al., 2007, 2008; Bailey et al., 2007). They used full-color, monocular HWD worn on the dominant eye, requiring the pilot to glance up to receive an uninterrupted stereoscopic view of the outside world. The display types used in these studies are as follows:

1. Baseline: Head-down EMM with no traffic or routing information.
2. Intermediate: HWD: HWD with no traffic, routing, or clearance information.
3. Advanced HUD: HUD showing virtual airport but no traffic, routing, or clearance information.
4. Advanced HWD: HWD with traffic and routing information (Arthur et al., 2007, 2008: Bailey et al., 2007).

After the experiment, the pilot completed a questionnaire regarding any technology usability issues experienced. In general, the consensus was that the devices were easy to use, were not overly complex, and were integrated well. The primary negative feedback consisted of how difficult it was to learn to use the device, as well as if the system should be used frequently (Bailey et al., 2007).

Arthur et al. (2008) tested combinations of three different hardware configurations, two different display modes (with or without head tracking), and either conformal or non-conformal FOVs (for the non-tracking mode only; see Figure 31). The pilots also reported a preference for the higher-resolution display and a preference for the open, see-through configuration. Also, the pilots ranked the Multi-Mode display higher than the Single-Mode and ranked the two 2-D modes above the 3-D Perspective, with the Text mode ranked last. For the 3-D Perspective Mode, pilots preferred the head tracking to be ON, but when head tracking was OFF, the pilots preferred the HUD FOV to the Conformal FOV.

Figure 31
HWD Display Conditions for the Usability Study



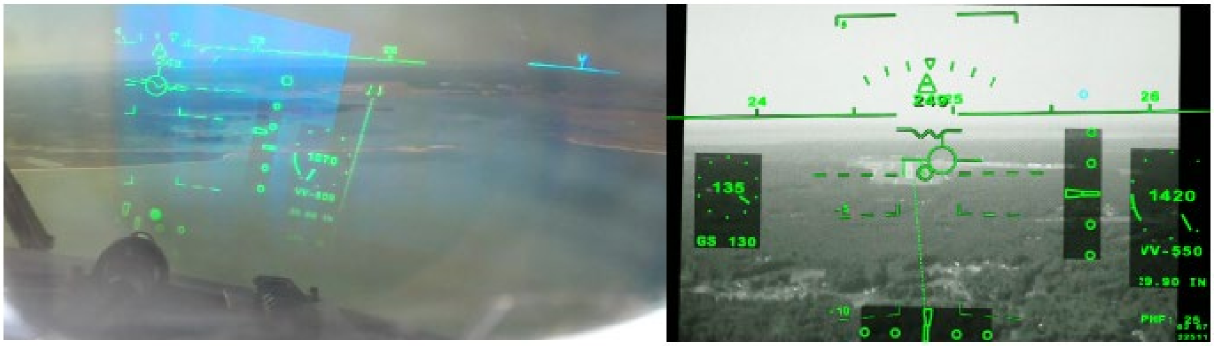
*(Arhtur et al., 2008)

In a study assessing the use of HWD for "HUD equivalence", investigators found that the use of HWD did not cause much eye strain or headaches, and they were comfortable to wear (Shelton et al., 2015). However, the important thing to note here is that the study did not actually use an HUD to compare with the use of an HWD. They did, however, use HUD-experienced pilots for these assessments (see Figure 32). These pilots rated the HWD as superior to the HUD. This study was conducted on a NASA Langley Beechcraft King Air (BE-200), which is a corporate-sized, twin-turbine aircraft that can be flown single-pilot. They used an HWD that used monochromatic standard HUD symbology in combination with non-standard HUD symbology in color (traffic was depicted in cyan diamonds, and the off-boresight horizon was presented in white; Figure 33). The images show the pilot's view through the HWD at 15 degrees right of bore-sight on final approach (left), and the HUD symbology on HWD when the pilot is looking directly forward (right image; Shelton et al., 2015).

Figure 32
BE-200 Cockpit with Pilot Wearing the HWD

*(For more information, see Shelton et al., 2015)

Figure 33
Pilot's View through HWD and HUD Symbology.



Shelton et al. (2015) evaluated taxi and approach using the HWD device with the Society of Automotive Engineers (SAE) HUD performance requirements and Minimum Aviation System Performance Standards (MASPS) for EFVS (DO-315). They included three approaches and taxi-in and taxi-out scenarios. An interesting point to note from this study was that some pilots experienced turbulence during their trials. The turbulence caused their heads to shake, which shook the HWD as well. This resulted in unstable images on the HWD due to system latency and jitter. Although minimal, this shaking did increase eyestrain and occurrences of headaches (Shelton et al., 2015).

HWD Usage During Taxi, Takeoff, Approach, and Landing

This section of the report reviews studies conducted to evaluate the use of HWDs in aircraft during taxi, takeoff, approach, and landing scenarios by evaluating pilot performance. It highlights the different performance measures used to study the efficacy of using EFVS on HWDs by pilots and highlights the results and interpretations from the articles reviewed. Both subjective/qualitative results, as well as objective/quantitative results, were included in this review to provide a more complete evaluation of different systems.

Influence on Flight Path Maintenance, Navigation Error, and Speed

Flight path maintenance can be evaluated by taking the Remote Maintenance Subsystem (RMS) of lateral and vertical deviations in flight or by centerline deviations on the surface. This quantitative performance measure can be applied to taxi, takeoff, approach, and landing, so the effects of different displays can be compared between these phases of flight. Average taxi speed and navigation errors, such as deviations from the ideal path and incorrect turns, are objective performance indicators but apply specifically to surface operations.

During surface operations, advanced HUD and advanced HWD configurations were found to have significantly lower deviations from the centerline compared with the EMM and Intermediate HWD configurations but had no statistical difference between them (Arthur et al., 2007). The other study, which included paper charts as the baseline and an Advanced EMM instead of the Intermediate HWD, found that the EMM, HUD, and HWD all had significantly less RMS error than the paper but with no significant difference between them (Arthur et al., 2008). The display types used in these studies were as follows:

1. *Baseline:* Head-down EMM with no traffic or routing information.
2. *Intermediate HWD:* HWD with no traffic, routing, or clearance information
3. *Advanced HUD:* HUD showing virtual airport but no traffic, routing, or clearance information.
4. *Advanced HWD:* HWD with traffic and routing information (Arthur et al., 2007, 2008; Bailey et al., 2007).

These studies used a full-color, monocular HWD worn on the dominant eye, requiring the pilot to glance up to receive an uninterrupted stereoscopic view of the outside world (Arthur et al., 2007, 2008; Bailey et al., 2007). Further, flight profiles were not significantly affected by display configurations, showing similar flight path maintenance behavior with baseline, HUD, and HWD displays (Thomas, 2009).

A study by Wilson et al. (2002) investigating command guidance versus situation guidance symbology found that the command guidance symbology produced significantly greater deviations from the centerline while taxiing. Ververs et al. (2000) found that a tunnel-in-the-sky symbology reduced vertical flight path error on approach when compared with a traditional Instrument Landing System (ILS) symbology. This finding was further supported by Prinzel et al.'s study comparing raster background with synthetic vision and fusing these with tunnel-in-the-sky symbology (2007). A similar, earlier study that compared different tunnel-in-the-sky symbology with different guidance symbology found no statistical difference in path maintenance between the display modes (Prinzel et al., 2004).

An interesting point by McCann et al. is how pilot preferences for higher zoom levels on EMMs reduce “look ahead” cues that facilitate taxi speed by showing the pilot what to expect ahead (1997). To alleviate this, they compared baseline paper chart navigation, EMM on HDD navigation, and a combination of an EMM with an HUD that had scene-linked HUD symbology as “look ahead” cues (McCann et al., 1997). They found that 26% of pilots chose the highest zoom level on the EMM, and 57% chose the second-highest, proving the pilots preferred the higher zoom levels; however, they also found the EMM+HUD condition significantly increased the average taxi speed, reducing the impact of the higher zoom level (McCann et al., 1997). Arthur et al. noted a significant increase in average taxi speed in all of the advanced display configurations compared with the baseline paper charts or with the baseline EMM (2008).

Navigation errors during taxi were found to be greatest when using paper charts or head-down EMMs (maps only) compared to advanced EMMs, HUDs, and HWDs with routing and clearance information (Figure 17; Arthur et al., 2007, 2008). Arthur et al. noted that while the advanced HUD produced the fewest navigation errors, the test crews using the advanced HWD were able to immediately identify and report their errors—those who made errors while using the paper charts or EMMs without routing did not notice their mistakes and continued on the wrong path (2007, 2008). Additionally, a different study found that an EMM+HUD configuration produces significantly fewer navigational errors than an EMM HDD alone, and the EMM alone produced fewer errors than baseline paper chart navigation (McCann et al., 1997).

Studies have shown that HUDs can support better path tracking than flying with HDDs. Pilots flying with HUDs have shown a decreased ability to detect runway incursions or other unexpected events (Haines, 1991).

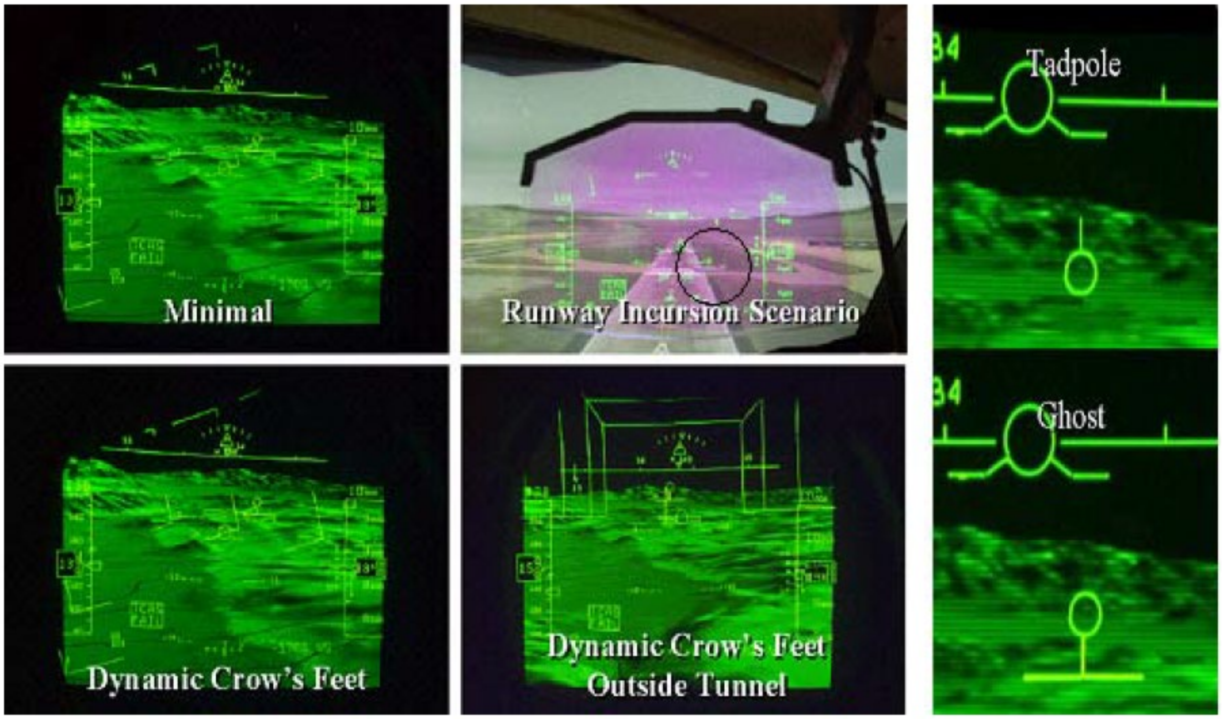
Detection of Runway Incursions and Taxi Conflicts

Unexpected events can occur in any flight mode, but runway incursions and taxi conflicts are specific to taxi, takeoff, approach, and landing. Runway incursions include unexpected planes or maintenance vehicles, while taxi conflicts can include aircraft collisions or near-miss turns on the taxiway.

Arthur et al. (2007) compared the four types of displays: EMM head-down, Intermediate HWD, Advanced HUD, and Advanced HWD; they found that one-third of all the taxi incursion events occurred while the pilots were using the HUD. Advanced HUD and Advanced HWD performed better for taxi efficiency and taxi safety. Taxi incursion events were lowest with Advanced HWD but highest for Advanced HUD.

In a different study evaluating SVS HUD symbology, Prinzel et al. (2004) found no decrease in unexpected event detection when participants utilized tunnel and guidance concepts during approach scenarios see Figure 34).

Figure 34
Synthetic Vision HUD Concepts and Tunnel Guidance Symbology.



* (This image depicts the runway incursion scenario; Prinzel et al., 2004).

In an experiment to test the efficacy of the supplementary use of enhanced vision and synthetic vision, HUD symbology made it difficult to spot the runway incursions, and the detection depended on the size of the incurring vehicles and their contrast to the surrounding environment. The HUD display concepts tested were shown to be not useful for runway incursion detection (Prinzel et al., 2007).

In an experiment that compared the tunnel-in-the-sky symbology to ILS guidance while aircraft are on final approach, Ververs et al. (2000) found no significant differences in terms of runway in sight, runway incursions, parallel traffic incursion, and turnoff traffic obstacle. In Beringer (2020; see also Beringer, 2016), participants were asked to perform Special Authorization (SA) Category (CAT) I approaches, three localizer approaches, and missed approaches in a high-performance, single-engine GA flight simulator. This study compared the use of two decision heights presented in three types of displays—HDDs, HUDs, and HWDs—each presenting with synthetic vision (SV). The SV was more beneficial in the case of missed approaches in mountainous terrains; however, it was not significantly beneficial for the initial approach. However, there were no significant differences among the three display types when comparing the success rates of the landings (Beringer, 2020). The results of these studies appear to be mixed and point to the need for additional research to understand how the use of different displays and display concepts affects runway incursion and taxi conflict detection.

Conclusion

This report provides a review of the existing body of knowledge on cognitive and physical factors in the use of HWDs, HMDs, and HUDs. It details the physical composition of an HWD, discusses human interaction with the HWD system, and finally, reviews the studies that evaluate pilot performance with the use of these displays in taxi, takeoff, approach, and landing scenarios.

This review includes relevant empirical findings from articles on topics pertinent to the use of HWDs by pilots in civil and military aviation. Relevant articles selected for review include topics on the use of HWDs in military and commercial aviation, HUDs in military, general, and commercial aviation, and the use of night-vision goggles.

HWDs comprise four essential elements: the hardware used to generate visual imagery (CRT, LED, etc.), optical configuration (monocular, binocular, or bi-ocular), head-tracking capability, and information type (symbology and pictorial presentations). The interactions between the pilot and the HWD can vary based on its design and structure. Therefore, the human factors related to these interactions are dependent on the different physical elements that may be part of an HWD system.

A necessary condition for the use of an HWD is that the user is able to clearly see the information displayed in the HWD while minimally obstructing the view of other visual elements in the cockpit (such as cockpit displays) and the OTW view. Display luminance and contrast, ocularity, and factors affecting accommodation and vergence were identified as critical to determining the quality of interactions between the human user and the head-worn device. These factors are essential for HWD design consideration to ensure smooth and efficient visual information processing for pilots using HWDs in support of pilot performance and safety.

The visual display of information should be presented such that it is clearly visible (even in the challenging viewing context of a cockpit) and in a manner that supports the interpretation and integration of the data into flight operations. The symbology used to encode and present this information plays a critical role in supporting processing effectiveness and efficiency. The luminance contrast between symbology and the background determines the ease of visual information processing. Moreover, the natural-mapping properties of the symbols presented can influence the interpretation of the information. Symbols that are poorly matched to the represented data can increase the demand on pilots' attentional resources, and interpreting the data may increase the risk of performance costs, such as spatial disorientation. Additionally, symbol stability and location on the HWD can affect the likelihood of detection, as well as the ease and speed at which the presented information is processed. The employed colors, speed of dynamic information presentation, and amount of information presented can affect the process of perceiving and interpreting visual data.

Evaluations of symbology should assess its ability to capture a pilot's attention when necessary, as well as to guide them toward appropriate response actions. Consideration should also be given to the mental resource costs of simple versus complex symbology; for instance, using easy-to-interpret symbology imposes less workload on the pilot than more complex data displays, thus allowing more resources to be available for allocation to the control of the aircraft and other relevant tasks.

The overlap in the imagery presented to the two eyes needs to be such that the total FOV of the user is not severely restricted. Smaller FOVs can increase the number and frequency of head movements for the pilot, causing increased fatigue and an increased risk of missing information. Larger FOVs reduce the number of head movements and are generally more comfortable for the user. Additionally, the HWD head-tracking system should be able to keep pace with the pilot's head movements and should refresh and provide necessary information quickly. Delays in information presentation/refresh can lead to disorientation and missed information.

Wearing a display device mounted on a helmet or on the head can introduce some physical constraints on the user. The weight and size of the device can affect the user's physical comfort at the points of contact on the head and face, change the center of mass of the head and thus reactions to force vectors, and induce strain on the neck and shoulders. The HWD projects a VE for the user's eyes, and this can cause some users to show symptoms of simulator sickness such as nausea, disorientation, and headache when multisensory input is not of similar degrees of fidelity and/or is not well synchronized.

The review of studies that evaluated pilot performance when using these displays indicated that pilot performance using HWD may be equivalent to pilot performance using HUD. There was no conclusive statistical difference in pilot performance between an HUD and an HWD. During taxi operations, both displays were shown to have better performance than traditional paper chart navigation and EMMs (head down, map only). Additionally, pilots reported increased SA and reduced mental workload when using an HUD or HWD compared to paper charts and HDDs. Thus, the HWD can be seen to have similar benefits as the HUD for taxi, takeoff, approach, and landing.

While this review covers many human factors concerns in the use of HWDs for aviation, there are still topics where further research is warranted. Some topics include the following: the use of HWD during specific low-visibility approach, landing, and takeoff operations (SA CAT I, CAT II, SA CAT II, CAT III), during advanced vision system operations, and during lower-than-standard takeoff minima operations. Human factors and pilot performance considerations associated with binocular rivalry, eye dominance, and other visual processing factors are recommended for future study. These studies should emphasize performance and can draw from the examples offered below. Table 9below summarizes pilot performance metrics, and Table 10summarizes simulator, flight, and airport metrics used in the prominent studies reviewed here.

Table 9
Experimental Pilot Performance Metrics

Measure Type	Performance Measure	Measure Used	Example
Subjective	Situation Awareness	SART	Arthur et al., 2007, 2018; Bailey et al., 2007; Prinzel et al., 2007; Thomas, 2009; Wilson et al., 2002
		1-7 pilot rating	Wilson et al., 2002
		3-point SART	Arthur et al., 2014
		SAGAT	Arthur et al., 2008; Prinzel et al., 2004
	Overall Awareness	Terrain awareness, taxi awareness, route awareness, etc.	Arthur et al., 2007
	Simulator Sickness	SSQ	Arthur et al., 2007, 2008, 2018; Bailey et al., 2007
		SSQ	Arthur et al., 2014
	Usability	Usability questionnaire	Arthur et al., 2008; Bailey et al., 2007
	Latency	Windshield Washer Test	Bailey et al., 2007
	Workload	USAF (USAFSAM Workload Scale)	Prinzel et al., 2004; Thomas, 2009
		AFFTC Workload estimate	Arthur et al., 2018; Prinzel et al., 2007
		NASA-TLX	Arthur et al., 2007, 2008, 2018; Bailey et al., 2007; Cheung et al., 2015
		1-5 pilot rating	Wilson et al., 2002
		NASA TLX & AFFTC 7-point subjective workload scale	Arthur et al., 2014

Measure Type	Performance Measure	Measure Used	Example
Objective	Navigational Errors	Lateral offset (in feet) between symbology and actual path taken	Arthur et al., 2007, 2008; McCann et al., 1997, 1998; Prinzel et al., 2007
	Taxi Conflict Events	# Collisions or near-collisions	Arthur et al., 2008; McCann et al., 1998
	Taxi Performance	RMS from centerline	Arthur et al., 2008; Wilson et al., 2002
		Average speed	Arthur et al., 2008; McCann et al., 1997, 1998; Wilson et al., 2002
		Route completion time	Arthur et al., 2008; McCann et al., 1998
	Runway Incursions	Runway incursion detection	Prinzel et al., 2004, 2007; Thomas, 2009
	Illegal Landings	Weather obscured visual cues required to complete landing from 100 ft. HAT (threshold)	Prinzel et al., 2007
	Touchdown Performance	Landing performance statistics of longitudinal distance from threshold, lateral distance from centerline, and sink rate	Arthur et al., 2018
	Threshold Crossing Performance	Root mean square error (RMSE) (glideslope, localizer, and sink rate deviation) and maximum values (glideslope, localizer, and sink rate deviation)	Arthur et al., 2018
	Flight Technical Error	RMSE for glideslope tracking	Arthur et al., 2018

Measure Type	Performance Measure	Measure Used	Example
		and sink rate deviation	
	Flight Path Performance	Vertical or lateral flight path errors	Prinzel et al., 2004; Thomas, 2009
	Altitude Tracking	Vertical error	Thomas, 2009; Ververs et al., 2000
	Communication Acts	# of communications acts between captain and first officer (FO)	McCann et al., 1998
	Position Recovery	% incorrect first control movement	Haworth et al., 1992
	Post-Experiment Questionnaire	Crew's response and ratings on wearable display equivalence between HUD & HWD	Arthur et al., 2014
	Target Location	Time to correct control movement	Haworth et al., 1992
		Elapsed trial time	Haworth et al., 1992
		Cumulative distance traveled to end of trial	Haworth et al., 1992
		Straight line distance from release to end of trial	Haworth et al., 1992
		Time until first hover achieved	Haworth et al., 1992
		Cumulative distance to first hover	Haworth et al., 1992
	Low Altitude Spatial Awareness	Elevation angle	Haworth et al., 1992
		Azimuth angle	Haworth et al., 1992

Measure Type	Performance Measure	Measure Used	Example
	Up-and-away Spatial Awareness	Elevation angle	Haworth et al., 1992
		Azimuth angle	Haworth et al., 1992
	Spatial Awareness	Degree error	Haworth et al., 1992

Table 10
Simulator/Flight/Airport Metrics

Simulator	Vehicle Info	Airport	Citation
Visual Imaging Simulator for Transport Aircraft Systems (VISTAS) III part-task simulator at NASA LaRC	N/A	Taxi operations at Reno/Tahoe International Airport in Nevada (KRNO)	Arthur et al., 2014
Used a silicon graphics Onyx RE2 computer to present the flight simulation and for data collection; a joystick built into the right arm of a chair was used to control the simulation	N/A	N/A	Foyle et al., 1995
Part-task simulator at NASA Ames Research Center; simulator was controlled using a side-stick, non-differential throttle, rudder pedals, and toe brakes	Boeing 737	Dallas-Fort Worth International Airport (KDFW)	Wilson et al., 2002
Evans and Sutherland SPX500 to generate the (OTW) scene and a Silicon Graphics IRIS workstation to generate the instrumentation and aerodynamics; the simulation was controlled using a two-axis joystick	N/A	N/A	Ververs et al., 2000
NASA-Ames' Advanced Concepts Flight Simulator (ACFS)	Wide-body, low-wing B757	Chicago-O'Hare International Airport (KORD)	McCann et al., 1998
Research Flight Deck (RFD) simulator at NASA LaRC; the simulation was controlled using a tiller, throttles, rudder pedals, and differential toe brakes	Boeing 757	KORD	Bailey et al., 2007
RFD motion-based simulator at NASA LaRC	N/A	Approach and other operations were conducted at the	Arthur et al., 2014

Simulator	Vehicle Info	Airport	Citation
		Memphis International Airport (KMEM)	
National Research Council's Advanced System Research Aircraft (ASRA, C-FPGV), with a fly-by-wire control system	The National Research Council ASRA is a modified Bell 412HP helicopter	N/A	Cheung et al., 2015
AFDD's fixed-based CSRDF's flight simulator; used a side-stick for controls	N/A	N/A	Haworth & Seery, 1992
	NASA Langley Beechcraft King Air (BE-200) aircraft	N/A	Shelton, 2015
RFD simulator on a motion-based platform at NASA LaRC, with instrumentation mimicking that of a commercial transport aircraft	N/A	Approach tasks at Memphis International Airport (KMEM)	Arthur et al., 2018
RFD simulator at NASA LaRC; the simulation was controlled using a tiller, throttles, rudder pedals, and differential toe brakes	Boeing 757	KORD	Arthur et al., 2007
Used several monitors to display a 737 flight deck, providing enough instrumentation for approach and landing tasks; used a yoke and column system for flight control	Display of a Boeing 737 flight deck	N/A	Thomas, 2009
Integration Flight Deck simulation facility at NASA LaRC	Simulated a Boeing B757-200 aircraft	N/A	Prinzel et al., 2007

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Appendix A. Evidence Table Culture

Evidence Table for Articles Reviewed for Evaluation of HWD in Taxi, Takeoff, Approach, and Landing Scenarios

Display Type	Pilot Performance Measure – Subjective	Pilot Performance Measure - Objective	Human Factors Assessed	Citation
HWD & HUD	Questionnaire, comparisons of subjective and objective measure	Navigational errors, rare events, taxi conflict errors	Situation awareness, mental workload, simulator, and HWD-induced sickness	Arthur et al., 2014
HUD		Navigation errors, taxi speed, taxi conflicts, route-following accuracy, route completion time	Workload, situation awareness	McCann et al., 1998
HUD		Forward taxi speed	Situation awareness	McCann et al., 1997
HUD		Altitude maintenance from RMSE from centerline	Attention Switching Cost	Foyle et al., 1995; Jones, et al., 2014
HWD	SA subjective metrics	Localizer and Box Glideslope dot error	Situation awareness	Shelton, 2015
HUD		Taxi speeds and RMSE from the centerline	Visual and attentional fixation or cognitive tunneling (referring to Command-Guidance Symbology)	Wilson et al., 2002
HUD		Flight path tracking, airspeed tracking, and response time		Ververs & Wickens, 2000
HUD & SVS			Measures Situation Awareness and mental workload	Prinzel et al., 2004

Display Type	Pilot Performance Measure – Subjective	Pilot Performance Measure - Objective	Human Factors Assessed	Citation
HUD & HWD	Taxi SA questionnaire, Simulator Sickness questionnaire	Taxi incursions, rare events, navigational errors, taxi performance		Arthur et al., 2007
HUD	Subjective measure of mental workload (using the AFFTC workload estimate tool, and post-test, using SWORD), subjective measure of SA (SART, and post-test, using SA-SWORD)	Path control performance, rare events - runway incursions, illegal landings, navigation errors	Mental workload and SA	Prinzel et al., 2007
HWD & HUD	Post-Run Questionnaires, pilot opinions	Approach/Landing Performance, Taxi/Departure Performance, workload and situation awareness metrics	Peripheral vision, Workload, Situation Awareness, Simulation sickness	Arthur et al., 2014
HWD & HUD		Approach/Departure Performance, Taxi Performance, Situation Awareness, Workload, Terrain Awareness, Task Awareness, Path Awareness, Communications Awareness	Situation Awareness, Workload, Terrain Awareness, Task Awareness, Path Awareness, Communications Awareness	Arthur et al., 2006
HUD		HDTS, BOSS, RSME	Simulator sickness, task load	Cheung et al., 2015

Display Type	Pilot Performance Measure – Subjective	Pilot Performance Measure - Objective	Human Factors Assessed	Citation
HMD		Time to correct, elapsed trial time, cumulative distance, straight line distance, time until hover, cumulative distance to hover	Spatial Awareness	Haworth & Seery, 1992