Visual aspects of advanced sensors and helmet-mounted displays

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ABSTRACT

Visually coupled systems such as helmet mounted displays are designed to improve aircrew situational awareness by providing timely flight, targeting and other information overlaid on real or sensor-derived views of the external environment. Data can be presented in monocular, biocular or binocular fashion and are associated with visual conflicts and potential ophthalmic problems. Restricted sensor spectrum, limits of resolution, inherent system latency, the displaced visual input from remote sensors and restricted field of view may contribute to ophthalmic symptoms in aircrew. Disruption to binocularity and reliance on monocular cues for depth perception and hyperstereopsis from sensor-induced convergence disparity may cause distance estimation problems, whereas inappropriate accommodative stimuli and ocular dominance factors are common causes of eyestrain. Binocular rivalry from discordant imagery to each eye may compromise visual performance via several mechanisms. This article discusses the potential visual problems associated with visually coupled systems and the challenges of integrating complex systems with the aircrew interface.

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ABBREVIATIONS

FLIR	Forward Looking Infra-Red
FoV	Field of View
HMD	Helmet-Mounted Display
I2	Image Intensification
IHADSS	Integrated Helmet and Display Sighting System
IPD	Inter-Pupillary Distance
IR	Infra-Red
JSF	Joint Strike Fighter
NV	Night Vision
NVG	Night Vision Goggles
VCS	Visually Coupled Systems

1.0 INTRODUCTION

The evolution of aircraft sensor technologies has enabled pilots to have increasing amounts of information readily available in order to improve situational awareness and facilitate a successful sortie. Visually coupled systems (VCS) are the interface between the visual and motor systems of the pilot with the aircraft and weaponry at their control, providing flight, targeting and environmental data to enhance capability and performance. Helmet mounted displays (HMDs) provide hands-free access to information from sensors about the aircraft, and may be linked to head orientation to provide real-time data linked to direction of regard without the pilot having to look into the cockpit[1]. Furthermore, information may be enhanced with the provision of night vision (NV) or infrared (IR) imagery. However, as newer aircraft such as Typhoon and F-35 Joint Strike Fighter (JSF) enter service with significant advances in both sensor and HMD engineering, there remain visual challenges that may manifest as symptoms. This report aims to provide a brief commentary on some of the potential visual problems associated with VCS and HMDs, and describe challenges that designers face in order to optimise the human-system interface and enhance aircrew performance.

2.0 HMD SYSTEMS AND INDUCED VISUAL PROBLEMS

2.1 Components of VCS and HMDs

The basic requirements of HMD systems include a mounting platform, which in practice is the aircraft helmet, to act as a point of attachment and stability to maintain alignment of the user's eye and the optical system. An image source generates the information to be provided to the pilot, such as image intensification(I2) tubes or forward-looking IR (FLIR) sensors, and imagery is transferred through relay optics and potentially combined with computer generated symbology to be presented as a final image to the eye(s). A head or eye tracker enables aircraft sensors to be slaved to the pilot's orientation and provide continuously updated information[2]. Data can be presented via HMDs to one or both eyes and systems can be classified as monocular, in which sensor imagery is presented to a single eye; biocular, in which two images are generated from a single sensor or multiple sensors but each eye is presented with the identical image from the same perspective; and binocular means the HMD provides an image to each eye from two sensors separated in space, thus providing perspective (Fig. 1). All types of system are associated with potential visual problems, although certain perceptual illusions are only encountered in particular designs of HMD setup[2,3].

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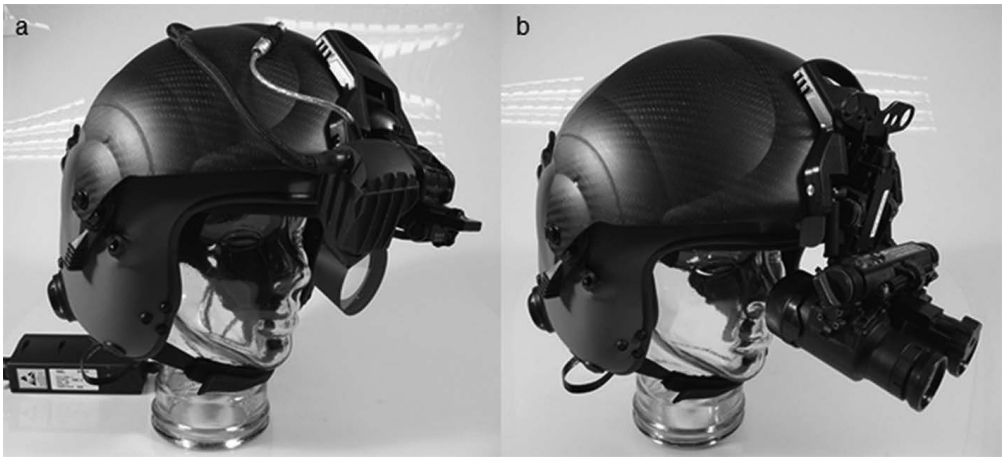


Figure 1. Monocular and binocular helmet-mounted display (HMD) systems; (a) monocular Day Head Up Display (D-HUD) used on the Puma 2 aircraft, (b) binocular Nite-Op night vision goggles.
(Images kindly provided by Air Equipment Integration Group, RAF Centre of Aviation Medicine).

2.2 HMD weight and musculoskeletal risks

A critical factor in HMD design relates to the weight being carried by the pilot on the helmet. Military pilots are exposed to high G-forces, and the additional weight of a HMD can increase the risk of musculoskeletal fatigue and neck pain, as well as potential for more serious spinal injury[4]. Furthermore, pilots may adopt compensatory head and neck postures in order to overcome HMD weight and place further stress on the their upper torso and neck[4,5]. The desire to minimise head-supported weight was a significant driver in the development of monocular HMD systems such as the Integrated Helmet and Display Sighting System (IHADSS) utilised by Apache helicopter pilots since the 1980s[6,7].

2.3 Vibration and helmet fit

HMD performance advantages rely on the critical alignment of the optical system with the user's eye, and therefore helmet fit is of paramount importance. Cockpit vibration is particularly pronounced in rotary wing aircraft[8], and compensatory eye movements may be ineffective at image stabilisation at low frequency, leading to visual blur or helmet slippage with partial or complete loss of the projected image[9]. Adequate relay optics, magnification and luminance contrast may mitigate against vibration-induced image loss in part, but meticulous helmet fitting is required to optimise performance.

2.4 Eye relief

Optical eye relief refers to the spatial distance between the last optical elements of the system to the eye, but physical eye relief is arguably more important. This is the distance between the last physical element to the eye, and should be sufficient to allow for any refractive correction (spectacles/contact lenses) or personal protective equipment such as oxygen masks or chemical, biological, radiological or nuclear protective masks[3]. If the optical system is too close to the eye it may compromise physical comfort, but too far away and the field of view (see later) will be compromised[2,10].

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2.5 System latency

All mechanical systems have an inherent temporal delay, and in the case of HMDs this is important in the head-tracking process. The head-positioning detection system provides this positional information to the aircraft sensor to alter its direction of regard, which then captures the visual scene and transmits the information through the optics to the display. The latency of this processing is determined in part by the 'slew rate' of the sensor, that is the temporal delay for the sensor to acquire the desired direction of regard related to the pilot's new head position[2]. Total system latency of up to 300ms is unacceptable in terms of performance, and most systems aim to keep latency below 50ms to avoid symptoms of motion sickness[2]. Comparisons with processing in the human visual system are difficult due to the multiple layers of neuronal networks, although visual evoked potentials record brain responses to visual stimuli within 50-100ms[11] and the vestibulo-ocular reflex can be as fast as 7-15ms[12]. Furthermore, the rapid processing of visual stimuli relies in part on the human brain making certain assumptions about the visual environment, which can lead to confusion and perceptual illusions in certain situations where the assumptions do not hold[10]. Despite advances being made in many areas of HMD design, system latency continues to be a significant problem, even in the most modern military aircraft such as JSF[13].

2.6 System resolution

System resolution is a key determinant of the success of HMDs. Resolution reflects the ability of the system to reproduce the detail of the ambient scene, and represents the ability to resolve fine detail. Visual acuity is the measure of resolution in the human visual system, and is commonly



Figure 2. Snellen chart for measuring visual acuity in the human visual system.

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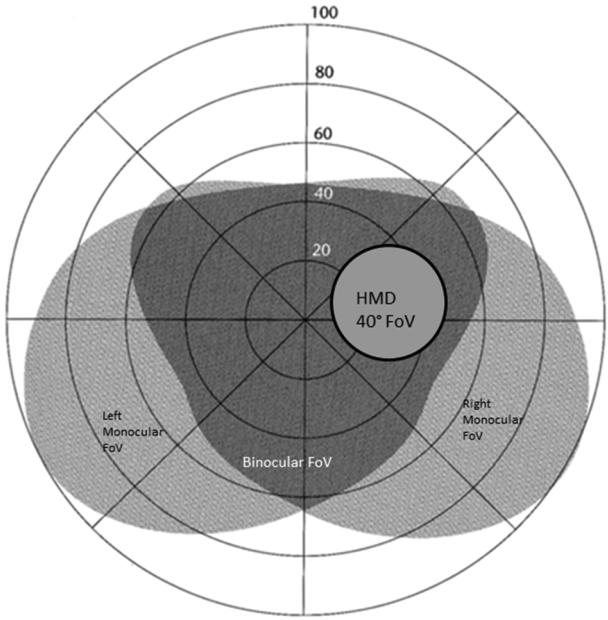


Figure 3. Human monocular and binocular field of view (FoV) and representative area of typical helmet mounted display (HMD) FoV (degrees).

described based upon testing with a Snellen chart, expressed as a numerator representing the distance at which the observer can correctly read a set of letters and a denominator representing the distance at which letters would be read by a clinically normal observer[14]. Therefore Snellen acuity of 6/12, for example, indicates that an individual can read letters at 6m that a normal observer could read at 12m. Normal human visual acuity is 6/6 (20/20 if the unit of measure is in feet) and many pilots will have better vision with acuity of 6/5 or even 6/4 (Fig. 2). Reduced resolution is a feature of almost all visual sensors, leading to images appearing blurred, lacking in fine detail and difficulty in recognition. Providing a sensor resolution in terms comparable with the human system is problematic, especially for FLIR (thermal) systems as parameters are confounded by the emission characteristics of the target object[7], although FLIR resolution is commonly described as approximating 6/18[15]. For pilots working with systems with a reduced resolution, the effect is an increased risk of visual fatigue and eyestrain, and may lead to deficits in height estimation, particularly in suboptimal environmental conditions[7,16].

2.7 Field of view

The field of view (FoV) is another factor of HMDs that may compromise visual performance, and relates to the maximum angle of view that can be observed. The normal human FoV has binocular and monocular components. Each eye individually can typically see 120° in the vertical meridian and 150° in the horizontal meridian (monocular field), and with both eyes open together the binocular FoV measures approximately 120° vertically by 200° horizontally, with a central overlapping binocular field and monocular areas at the horizontal periphery (Fig. 3)[17]. A large FoV increases the information available to the observer, although most HMD systems are constrained by technical parameters such as weight, size, resolution and placement and consequently provide

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a FoV that is significantly restricted compared to the normal human unaided condition[3]. The monocular IHADSS HMD system offers a rectangular FoV limited to 30° vertically and 40° horizontally[2,7], the binocular Typhoon and TopOwl systems provide 40° fields[2] (Fig. 3). Pilots typically want the FoV to be as large as possible, as operating with a reduced FoV is associated with impaired performance on tracking tasks[18], disturbed visual perception in terms of depth perception, distance estimation and size estimation[19,20], visual fatigue and eyestrain. Furthermore, the need for an increase in compensatory head movements may pose risks of musculoskeletal injury[21], and when a point of interest is identified, pilots may focus on the area of interest at the expense of maintaining a broader situational awareness[7].

2.8 Image chromaticity

Many visual sensors provide information and symbology in a monochromatic format, i.e. without variation in hue. Consequently, variation in luminance contrast is vital for the pilot to interpret the data[3]. The chromaticity of the sensor depends on the phosphor within the system, and most have a spectral distribution close to the sensitivity of the human eye, which has peak sensitivity of approximately 555nm in light-adapted conditions and 507nm in the dark-adapted state[3]. For example, the IHADSS imagery uses the P43 phosphor with peak spectral sensitivity of 543nm, close to that of the human eye[3]. Pilots are used to flying with imagery presented in monochromatic format, and in practice it rarely provides significant visual symptoms, although challenges arise given that background luminance affects the gain of the system and therefore bright cultural lighting may reduce the ability to detect more subtle luminance contrast effects such as contour gradients used in height estimation, or to attend to cockpit stimuli[3,10]. It is possible to add false colours to imagery from FLIR sensors, for example, although this may add more confusion to the visual demands of the aircrew. Furthermore, the reliance on luminous intensity of the system to provide visual information prevents any problems for pilots who may have any degree of colour vision deficiency.

2.9 Sensor spectral sensitivity

Despite the very narrow peak spectral sensitivity of the human eye, the visible part of the electromagnetic spectrum is approximately 400-700nm (0·4-0·7μm), with colour perception depending on the exact spectral components of the light stimulus. Infra-red sensors systems such as FLIR have sensitivity in the range 8-12μm, and therefore the representation of visual space generated by FLIR is completely different to a normal visual perception[7]. The image synthesised by a thermal imaging system depends on the reflectance and absorbance characteristics of the object of regard, and the ambient temperature. Consequently, a particular visual scene may generate contrasting visual information for the pilot depending on whether or not the thermal imaging system is in use. Although information generated via such a sensor is better than no information at all, it can be a source of frustration that objects may not be easily recognisable, particularly if the ambient temperature or humidity degrades the generated image. In certain conditions when the background and atmosphere have similar thermal signatures 'thermal cross-over' occurs and all scene contrast is lost, rendering the pilot blind using the FLIR system[10]. Coupled with the reduced resolution of visual systems, pilots endure visual fatigue when flying with such systems, although becomes easier with adequate training and experience, and the improved resolution of more modern systems will only serve to improve matters further.

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2.10 Displaced spatial reference

The visual sensor providing information to the pilot is often located remote from the cockpit, providing a perspective to the pilot displaced from the normal head position. In Apache, the FLIR night vision sensor is located on the aircraft nose, approximately 3m anterior and 1m inferior to the pilot's eye[7], and the FLIR sensor in Eurofighter Typhoon is positioned outside the cockpit on the left side of the aircraft[22]. Remote sensor positioning enables uninterrupted views around the aircraft, although can induce visual illusions of parallax and affect distance/height and motion estimation[7,23]. Operating a system from a remote perspective is a relatively straightforward skill to learn, although the challenges in aviation relate to the requirement for continual re-orientation of the pilot to ensure they are aware of the aircraft position in space, and the changes in perspectives when transitioning between systems[7].

3.0 HMDS AND VISUAL PERCEPTION

3.1 Depth perception

The ability to perceive depth relies on both binocular and monocular cues. The distance between the two eyes is the inter-pupillary distance (IPD), and the horizontal separation of the eyes generates a slight disparity of the retinal image formed by the visual scene in the two eyes[24]. This forms the basis for stereopsis, a manifestation of higher cortical processing, and a binocular cue for depth information[10]. Stereopsis is useful for resolving depth information up to approximately 60m away from the observer, as beyond this the light rays arriving at the retina are essentially parallel and retinal disparity becomes negligible[6,10]. Depth perception does not rely on stereopsis alone and several monocular cues can be utilised also (Table 1). Monocular and biocular systems cause a complete loss of stereopsis and therefore the reliance on monocular cues[6,7], which can be improved with training and experience, although the ability to interpret monocular cues can be impaired by the reduced resolution of the HMD systems which degrade such cues as texture, gradient, shading and contours[10].

Table 1
Monocular depth perception cues[10]

Monocular cue	Explanation
Relative size	*Knowledge of the approximate size of an object can enable estimation of distance relative to other objects*
Interposition	*If one object is obscured by another, the former appears behind or more distant than the latter*
Geometric perspective	*The perception that a pair of straight parallel lines appear to converge in the distance, e.g. railway tracks*
Motion parallax	*The relative with and against motions of objects in relation to the observer are related to distance*
Texture and contours	*Textural detail perceived by the observer depends on distance: the closer the object the greater the texture detail*
Light and shading	*The closer an object is to a light source, the brighter it appears. Objects casting shadows on themselves and other objects provide information about the position of the object and light source relative to the observer*

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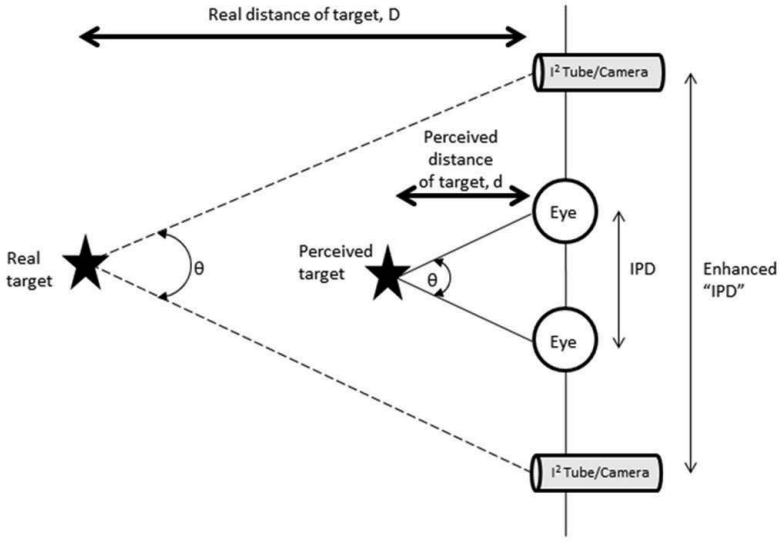


Figure 4. Hyperstereopsis. The distance between I2 tubes/cameras is greater than IPD. In order to fixate on a target at distance D the observer must converge as if the target was located at distance *d*, thus the target appears closer to the observer.

3.2 Hyperstereopsis

The problematic perceptual phenomenon of hyperstereopsis is unique to binocular systems and arises in situations where two input sources (such as I2 tubes) are located at a greater than normal IPD. The average human IPD is approximately 64mm whereas the separation of input sources on the TopOwl system is 286mm (effectively four times normal IPD)[2,24]. Hyperstereopsis is the result of fusing two images of an object into a single percept when each image results from a different lateral perspective separated by a distance greater than the IPD, leading to exaggerated lateral dimensionality[25,26]. The phenomenon arises due to a discrepancy in the convergence angle to an object from the horizontally-displaced inputs compared to the 'normal' IPD[10,27] (Fig. 4). The perceptual result is that objects appear closer than they actually are, giving an illusion to pilots that the ground may be rising up to them[28], or that when sitting in the cockpit on the ground, it may appear that ground level outside is at chest height, with potential impact on height estimation and rate-of-closure on landing[10]. Furthermore, additional visual illusions from hyperstereopsis include the perception of the ground sloping up toward the observer, 'creating a bowl' or 'crater' effect[10]. Hyperstereopsis is predominantly a manifest perception within a few hundred feet, as the relative convergence between inputs decreases with distance from the observer[2,10,28]. Habituation and adjustment to the effects of hyperstereo can occur within around 5-6 hours of training[27], although it remains unclear whether adjustment is a perceptual adaptation or a behavioural compensation[27,28].

3.3 Accommodation

In order to focus upon objects nearer to the observer than optical infinity the human eye accommodates to adjust focus. Stimulus blur and chromatic aberrations are thought to be the stimulus for the ciliary muscle of the eye to contract, releasing the tension on the suspensory ligaments of the crystalline lens and allowing the lens to adopt a more convex shape to increase the dioptric refractive power of the eye[24,29]. Furthermore, the accommodation reflex is also linked to ocular convergence and pupillary

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constriction, such that if the object of regard moves closer to the observer, the eyes converge to align the retinal images of each eye and the pupil constricts to reduce optical aberrations[24]. Given no stimulus to accommodate, the traditional view was that the normal emmetropic (without refractive error) eye would focus at optical infinity, although it is increasingly understood that in darkness or in an empty field (such as that experienced by a pilot in a clear sky), accommodation may lapse to a resting position of approximately 0·5-2m[29-31]. The optical systems of HMDs are typically such that imagery and symbology are collimated and therefore should be in focus to the aircrew without accommodative effort[3]. The convergence response initiated by accommodation may potentially be a problem if shifting attention to the cockpit or if the pilot has a small degree of refractive error, leading to mis-alignment of the imagery and ghost-images[3,29]. In addition, despite the fact that HMD image combiners are transparent, if for any reason the combiner becomes visible, for example due to helmet mis-alignment or dust on the combiner, then there may be a stimulus to accommodate and misinterpretation of the imagery/symbology[29]. Involuntary accommodation may also be induced simply to the knowledge that the observer is looking through a combiner, and mental processing of collimated images also induces accommodation of up to 1·26 dioptres (equivalent to about 0·8m)[29].

Some of the adverse effects of inappropriate accommodation may be preventable. A study of the dioptre focus settings of 20 helicopter pilots after routine pre-flight setup found a range of focus settings from 0 to –5·25 dioptres (mean –2·28d)[32]. The accommodation required by the pilots to overcome the inappropriate focus settings was felt to be a source of headaches and visual discomfort during long sorties. Particular care should therefore be taken by aircrew to ensure that focus settings of their optical systems is appropriate to their refractive needs to prevent symptoms. More serious issues with 'inappropriate' accommodation may occur with the blurring of distant objects and alterations in the apparent size of objects, leading to errors in distance or height judgement[27]. Misinterpretation of visual cues due to accommodative factors may have played a role in instances of controlled flight into terrain and other aircraft accidents[29].

3.4 Ocular dominance

A potential problem with monocular systems, or bi(n)ocular systems utilising monocular symbology is that of ocular dominance. This refers to the situation of preference of the visual input of one eye over the other in terms of fixation and attention[33], and is associated with preferentially using one eye rather than the fellow eye during periods of monocular viewing[6,34]. The majority of the population are right eye dominant, accounting for the right eye design of IHADSS and the presentation of symbology to the right eye in many systems[6]. However, there is the potential for left eye dominant aircrew to have difficulty in attending to a right eye display, and this has been linked as a contributory factor to eyestrain and ocular discomfort after using monocular systems. Whilst there is evidence linking ocular dominance to tracking ability and other cognitive skills[35,36], there are no reports of impaired IHADSS targeting or pilot proficiency as a result of ocular dominance issues[6].

3.5 Binocular rivalry

A related but more problematic issue is that of binocular rivalry. In the case of dissimilar visual input to the two eyes, the brain may be unable to fuse the two images into a single percept, leading to the suppression of one image and attention to the other image[10]. As previously discussed, a small degree of horizontal disparity provides some perspective and enables stereopsis, but there are limits to the differences in retinal images that can be fused, and in order to prevent double vision (diplopia) suppression of one image occurs. This is relevant to HMD design, especially with monocular devices which enable viewing of the normal environment through the uncovered

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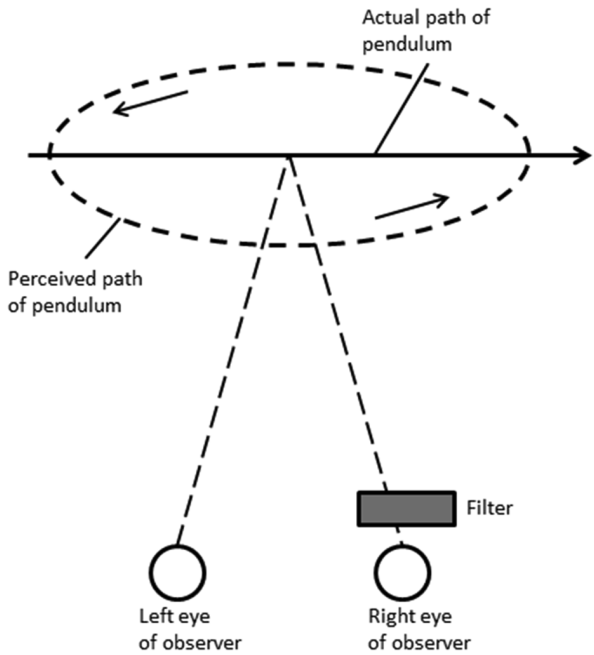


Figure 5. An illustration of the classical demonstration of the Pulfrich effect. A pendulum oscillates in a plane parallel to the observer. When a neutral density filter is placed before the right eye of the observer to induce a luminance contrast difference between the two eyes, the pendulum appears to move in an elliptical path, approaching and receding from the observer. (Adapted from Qian and Ersen, 1997[43], with permission from Elsevier)

eye and an image via the HMD eyepiece which may differ in resolution, colour, luminance, field of view, motion and/or perspective[6]. Binocular rivalry is not limited to monocular systems, as unilateral symbology in biocular and binocular HMDs may be problematic when delivered over a normal or image-intensified view of the outside world, or if the images to the two eyes are misaligned[10]. Binocular rivalry appears to be a manifestation of higher cortical rather than retinal neural processing, and therefore the image that the viewer perceives can alternate with variable periodicity and is amenable to conscious attention switches[10], albeit with considerable individual differences. Several factors may influence the duration of which a particular rivalrous image is perceived, including ambient scene complexity, HMD resolution, HMD field of view, HMD luminance, ambient environment luminance and HMD contrast[37].

The Pulfrich effect is a particular binocular visual illusion whereby an object moving in a plane parallel to the observer appears to approach or recede from the viewer, and is noticeable when there is difference in luminance presented to each eye, exactly the situation if observing an object through an image intensifier via one eye and through the unaided eye simultaneously[38] (Fig. 5). Furthermore, viewing through a night vision device with one eye only can lead to monochromatic adaptation, or 'brown eye', an uncomfortable visual effect noticeable when transitioning from having one light adapted eye and one dark adapted eye to both eyes viewing the same scene, potentially causing temporary loss of situational awareness[7]. Binocular rivalry has a negative impact on visual performance in terms of increased reaction times and unnoticed signals, and although observers are not always conscious of these performance limits, alternations of image may be perceived[39]. Nearly two-thirds of Apache Ah-64 pilots using the IHADSS system reported unintentional image alternations during flight, although 75% stated being able to switch attention easily from one eye to the other[40].

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3.6 Symptomatology

Given the many potential visual problems with HMDs, especially with monocular systems, it is not surprising that aircrew do report visual symptoms when using these systems. Aircrew surveys are a common mechanism for researching what is experienced in the 'real life' of day-to-day aviation, many of the reported issues are non-specific in nature, such as fatigue and headache[6]. A 1990 survey of 58 Apache pilots found over 80% state at least one visual complaint with the IHADSS monocular device, with 'visual discomfort' the most common feature, as well as headaches, blurred vision and disorientation whilst flying in up to 20% of respondents, with symptoms persisting after flight in many[39]. A larger study of 216 Apache aircrew reported at least one visual complaint in over 90% of respondents either during or after flight using a monocular system, with symptoms independent of pilot age or recorded flying hours[40]. Misjudged height and slope estimation, undetected drift and illusory drift were noticed by over 70% of pilots, although the Pulfrich effect was felt not to be major issue. Maintaining an adequate field of view due to helmet slippage was also considered a problem. NVG are also associated with visual symptoms and optical illusions, including impaired acuity and height estimation, and dynamic illusions such as undetected aircraft drift or illusory drift in up to 25% of pilots[41].

Most pilot surveys of visual symptoms have been carried out in peacetime, although the spectrum of visual complaints is different during combat aviation. A study of helicopter pilots in the 2003 Gulf conflict found a significant reduction in reported symptoms, especially for static and dynamic illusions, and visual discomfort and disorientation/vertigo after flying[42]. The differences in visual problems between combat and training flight are reportedly related to other distractors in combat situations, and a conscious effort to maximise proficiency with the aircraft systems during peacetime, leading to heavier reliance on the HMD imagery and increased associated illusions and symptoms[6].

4.0 SYSTEM INTEGRATION

Having a dual sensor capability providing both an image intensified NVG view and thermal-sensitive FLIR imagery would provide aircrew with an increased range of environmental conditions in which to operate. However, integrating these disparate systems with useful symbology represents a significant challenge to the aviation community[28]. Apache helicopter pilots use the monocular IHADSS system to view FLIR imagery and are required to rotate the system out of the line of vision to accommodate helmet mounted NVG. Binocular helmet systems such as in Typhoon and the TopOwl system use two laterally offset helmet-mounted sensors to project imagery onto the visor, and biocular systems such as that in development for JSF provide a single image to both eyes on the visor. Attempting to present imagery from both I2 and FLIR systems simultaneously therefore encounters several integration challenges, both in terms of the significant difference in the spectral characteristics of the imagery and the perspective distortion induced by the displaced positioning of the FLIR sensor. The presentation of dissimilar images to each eye that cannot be fused induces the conditions for binocular rivalry, leading to alternation between the two images and suppression of one image, which requires considerable effort to bring under conscious control. Differences in system latency between a 'real-time' I2 image and a temporally delayed FLIR image will make reconciling the imagery very difficult, and the choice of which eye/sensor to overlay symbology upon will also influence which image is attended to predominantly. Furthermore, given the conditions required to induce effects of hyperstereopsis and binocular rivalry, it is not possible under current configurations to experience both optical scenarios simultaneously, although switching between hyperstereo-generating I2 images and displaced FLIR images creates an altered spatial reference frame to which the pilot must rapidly try and adapt[28].

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5.0 CONCLUSION

The advanced sensors and VCS of modern aircraft provide information to aircrew to enable an increased situational awareness and the ability to operate in a wider range of environmental conditions. However, the design and optical presentation of imagery and symbology in these systems leads to potential visual conflicts and illusions, which may be significant enough to induce symptoms both during flight and persisting after the sortie. System optics, resolution, latency and field of view are only likely to improve with time as technology advances, but overcoming ocular dominance, binocular rivalry, hyperstereopsis effects and perspective distortions represents a significant challenge both for manufacturers to overcome in the design and implementation stages and for aircrew themselves to maintain their situational awareness and operational effectiveness.

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All views expressed are those of the authors.

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