OPTICAL INTERACTIONS OF AIRCRAFT WINDSCREENS AND HUDS PRODUCING DIPLOPIA

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Background:

The Air Force is in the process of evaluating new, wide field of view heads-up displays (WFOV HUDs) capable of presenting an enhanced array of visual imagery to pilots of modern aircraft. The wider fields of view through the WFOV HUD optics are achieved by using either conventional optics (as in the AFTI HUD), or holographic optical components (as in the LANTIRN HUD) to enlarge the binocular portion of the field of view (BFOV). In each of these designs, the portion of the FOV available for simultaneous use by both eyes, and the total instantaneous FOV is significantly larger than that found in "standard" HUDs.

The Problem:

Several pilot complaints have been received concerning double vision (diplopia) experienced while using LANTIRN F-16 HUD serial number 007 in a test aircraft. Specifically, complaint was made of seeing two targets while maintaining a single image of the display-generated aiming symbol. Statements have also been made concerning the doubled appearance of the pipper while maintaining a single image of the target. At least one pilot stated his depth perception was "different", and the world "appeared flatter." These complaints are based on visual errors induced in the pilots' binocular (two-eyed) visual system by the HUD and canopy optics. Not unreasonably, the complaints generated high-level concern about the utility of WFOV HUDs in general, and holographic HUD optical systems in particular. This paper will explain why these visual problems were experienced, and recommend some solutions for any WFOV HUD system, whether it includes holographic optics, as in the LANTIRN system, or "conventional" optics, as in the AFTI system.

The Eye -- Visual Physiology:

Whenever we look directly at an object or target, light from the target is focussed by the eye's optical system to fall on the retina. At the same time, each eye rotates slightly so the images fall on a particular part of each retina called the "fovea." Even though there are two images (one in each eye), we see only one object because nerves from the fovea eventually merge into only one perceptual area in the brain. Each of the two eyes has been mapped to show all possible retinal locations where only one image is perceived when both eyes receive similar appearing images. These retinal locations are called "corresponding points." The foveas are an example of two corresponding points. There are many more, distributed symmetrically about each fovea. Whenever fairly similar images are focussed on corresponding points in each eye, we see only one picture. This ability of our visual system to make one perceptual image from two retinal images is called "fusion."

Any well-engineered system is constructed with certain tolerances to error. Our eyes are no different. Each corresponding point has a small area surrounding it (Panum's area) which can tolerate a little misregistration of the image. Although we don't see double if the images fall outside the corresponding points but within Panum's areas, we do see this misregistration as a change in apparent depth of the objects. Images falling on nasal portions of Panum's areas are seen as being farther away in space than images falling on temporal portions. This disparity in the relative positions of similar images falling on each retina is also called "stereopsis" or depth perception.

Depth perception is affected by several cues, but the most important and most sensitive one -- which uses information from both eyes -- is stereopsis. Stereopsis also happens to be the only depth perception cue tested on flight physicals. Figure 1 illustrates how stereopsis works. Assume the eyes are looking at point B, so that target is imaged on each fovea. Light from point A also enters the eye, but is imaged on the retina a little distance from B. Laboratory experiments have shown that if the angle between these two rays of light entering the eye is as small as two seconds of arc, people will see point A as being closer than point B. This misregistration of images on the retina is sometimes called "retinal disparity", or "parallax."

If the parallax angle exceeds a certain amount, the images no longer fall within Panum's Area, and double vision will result. If point A were sufficiently far from point B, an observer looking at point B would see two images of point A. If the observer alternately closed one eye then the other, the image of point A would appear to jump back and forth. This jump or motion parallax is due to the misalignment of the object with our normal lines of sight. You can test this by looking (with both eyes) at a clock or other object on a distant wall. If you place your thumb in your line of sight, you may see two thumbs while you continue to look at the clock. If you alternately close your eyes, you will see your thumb jump back and forth. If it weren't for the built-in tolerances in our visual system, we would always see two images of any object not directly in our lines of sight.

All of this can be summarized: if the optical distances of two targets near our visual axes are relatively similar, we will see the two targets at the same depth. As the difference in these optical distances increases, we begin to experience stereopsis (see depth between the targets). At some point, the parallax is sufficient to cause diplopia or double vision of one of the targets (the one not directly viewed).

The HUD -- Affects Both Symbology and Target Images:

But why should a HUD cause diplopia? The answer is fairly straightforward. HUD imagery is generated on the face of a CRT. Light from the CRT passes through collimating optics so the light rays are rendered parallel. These parallel rays are then reflected from a combining glass to enter our eyes. Parallel light rays cause our eyes' lines of sight to orient themselves so they are also parallel. HUD imagery is seen as a virtual image, hanging in space. (The image is called "virtual" because its light really doesn't come from the place where you see it; here, the light is coming from the HUD rather than the point in space at which it is perceived.)

If the HUD is properly collimated, imagery will be seen at optical infinity, in the same place as the target in the real world. No double vision should be experienced because the images of distant real targets are also formed by parallel rays of light, and there is no parallax between the images. However, if the HUD is improperly collimated, the light rays leaving it may diverge or converge. In any case, if the convergence or divergence is sufficiently different from the parallel rays of light from the target, the images will fall on non-corresponding retinal points, and the pilot will see double images. Exactly which image is doubled depends on what the pilot examines:if he looks at the real world target, the reticle will double; if he looks at the reticle, the target will double. The pilot's visual system has absolutely no choice. If he passed his flight physical vision examination, and if the angular separation between light rays from the target and light rays from the symbology differ by more than a few milliradians of arc, he will experience diplopia of one image or the other.

Fortunately, HUD specifications recognize this possibility, and usually restrict parallax errors to less than three milliradians eye convergence and one milliradian or less eye divergence. Apparently, we can tolerate this amount of misregistration or disparity in "standard" HUDs without seeing double. However, the HUD quality control standards all assume the target is at infinity, so they strive to place the symbology image at infinity. You will see in the next paragraph that the target image is usually not at infinity because of the optical effects of the canopy. The LANTIRN HUD which caused the visual problems also caused a slight convergence of light rays from the HUD symbology, (causing the eyes to slightly diverge in order to fuse the symbology).

The Canopy -- Affects Image of Target Only:

This far, we have seen that diplopia can be caused by the improper collimation the light rays forming HUD symbology. There is another possible cause of diplopia, even when the light from the HUD is properly collimated. The other major cause is the curved canopy. The F-16 canopy is a fairly thick (about 3/4 inch) piece of material consisting of three different kinds of plastic (in the laminated version), or an equally thick sheet of polycarbonate (in the monolithic version). Each of the current vendors manufactures his canopies using methods which result in parts which are optically different from each other. One optical effect common to all curved canopies is the formation of a very weak "minus" or "negative" or "concave" lens in the forward area. Concave lenses cause previously parallel light rays to become divergent. In some canopies, this moves the optical position of the object from infinity to as close as 40 feet. The canopy on the aircraft with the LANTIRN HUD caused a slight divergence of light rays from the target, as if they came from a distance less than optical infinity.

But why don't we see double when we look through currently accepted F-16 canopies without interposing a HUD in our line of sight? A question fairly easy to answer. Our eyes adjust by turning slightly inwards to image the deviated rays on corresponding retinal points. Since all the rays are deviated more or less equally, and since there is no undeviated reference image, our eyes' tolerances accept the canopy-transmitted image of the world. Sometimes the world looks a little blurry or wavy, but we usually don't see double. If our pupils were very much larger, if the canopy were a little worse, or if conflicting image information were present at the same time, we would indeed experience diplopia.

<u>HUD + Canopy + Eye Optical System:</u>

Figure 2 shows how the HUD affects both light from the target (by refraction) and light from the CRT (by reflection). The canopy affects only light from the target (by refraction). If the canopy-induced vergence of light rays from the target is sufficiently different from the vergence of the light rays from the HUD symbology, diplopia will result. In other words, diplopia can be experienced when looking through either a perfectly collimated HUD and a canopy with some measurable parallax error, or a misaligned HUD and a "perfect" canopy. Specifying perfect parallelism of HUD-generated light rays is not necessarily the goal. The goal should be the attainment of comparable vergence effects of canopy and HUD on both target and symbology.

Measurements of the transparency and LANTIRN HUD aboard the F-16A which caused the pilots to complain of diplopia revealed that the LANTIRN HUD vergence error and the canopy vergence error were additive. Pilots flying this aircraft experienced more than five milliradians parallax error between target and symbol through certain portions of their field of view.

The optical effects of pupil-forming and non pupil-forming systems (holographic HUDs and conventional HUDs) are covered elsewhere in the Proceedings, as are relative advantages and disadvantages of wide instantaneous overlapping fields of view.

Suffice it to say that the smaller the instantaneous overlapping FOV, the less the opportunity to see double because diplopia is experienced only while the eyes are in the overlapping IFOV. Of course, the converse is true -- large overlapping IFOVs increase the probability of seeing double if there is a parallactic error somewhere in the system.

At present, all F-16 canopies are measured to determine how much angular deviation they will impart to a light ray passing through the canopy. This sighting error measurement is made only from the cyclopean eye position, located near the cockpit "design eye." All current USAF pilots have two eyes, located about 65mm apart (about 1.25 inches on either side of the cyclopean eye position). This separation of our eyes means our lines of sight pass through the canopy about 2.5 inches apart. Because of the minus lens effect mentioned in the previous paragraph, and because of the point-to-point variability in angular deviation within any single canopy, each eye then experiences a different vergence vector when viewing objects external to the cockpit. This vergence vector varies as the pilot looks around the field of view available for binocular vision. As indicated previously, our eyes are extremely sensitive to these tiny vergence-induced retinal displacements. At the present time, no canopy specification for any current USAF aircraft include vergence (collimation or parallax) limits similar to those included in HUD specifications.

Some Solutions

Several possible solutions may be considered, including introducing more stringent optical specifications for canopies, substituting flat-plate windscreens for curved transparencies, and reducing the binocular field of view of the HUDs. The best solution appears to be one which considers both canopy and HUD optics as a system, with specified limits of binocular parallax for the entire system rather than for each of the components. This could allow canopies and HUDs to be matched so their errors could cancel each other out to some extent. The logistical problem associated with this proposal is not trivial as each canopy's specifications would have to be matched with an appropriate HUD, within certain tolerances. However, each F-16 canopy is presently measured for "nameplate values" to input to the fire control computer of the particular aircraft on which it is mounted.

Measurement of the F-16 canopy-induced parallax can be done with equipment similar to that in use for measuring F-16 angular deviation. The measuring instrument should be located so it scans from points about 1.25 inches on either side of the cyclopean eye position. Angular deviation data from each matrix of values obtained from right and left eye positions can then be combined to show the disparity or parallax for each viewing angle. Of course, the effects of lateral displacement would introduce an error in these calculations, so only "pure" angular deviation should be measured.

Marconi Avionics have indicated that they could adjust the vergence of their WFOV HUDs to correspond with the vergence effects of the "average" F-16 canopy. If the remaining individual canopy errors exceeded the visual system's tolerance, an additional lens or other optical modification could be made to match the HUD to the canopy. The Air Force Aerospace Medical Research Laboratory (AFAMRL) has measured a series of F-16 canopies to determine their binocular disparity, and is now cooperating with the F-16 SPO and Marconi Avionics to determine whether a single correction would suffice for the majority of WFOV HUD-Canopy combinations. The tolerances allowable for the system depend on the visual systems' ability to maintain a single image when the canopy and WFOV HUD optics cause some parallax error. Unfortunately, tolerance limits of this type have not as yet been determined for the specific conditions encountered with aircraft WFOV HUDS and canopies.

Published threshold values are either questionable or gathered under circumstances inappropriate for generalization to F-16 HUD application. Thus, the F-16 SPO asked AFAMRL to conduct its own study.

Test Objectives

1. To determine the limits of the region of single vision as indicated by the horizontal diplopia thresholds of positive and negative disparity.

2. To determine the extent and nature of the distribution of individual differences in a Flying Class II Vision Population.

General Methods: Experiment

Definition: Optical distance is expressed in terms of the angular deviation of the eyes from the straight-ahead. Positive disparity means that a non-fixated object is optically nearer than a fixated object. Negative disparity means that a non-fixated object is optically farther than the fixated object. The diplopia effect threshold is that degree of disparity which induces a report of double vision <u>or</u> a binocular suppression effect on 50% of its presentations to an observer.

Equipment: The equipment consisted of a computer controlled HUD emulator which could superpose a luminous line (symbology) on a distant, out-the window scene. The optical distance of the symbology was adjusted to be either nearer or farther than a conspicuous vertical structure (a light pole) in the scene.

Subjects: A total of 32 persons were tested. All were volunteers from AFAMRL, ASD/EN and ASD/YP. All met at least Flying Class II Vision Standards and, further, none wore contact lenses, since pilots may not wear them.

Task: On each trial, an observer fixated a distant target and indicated whether or not a briefly-presented luminous line (the superposed HUD symbology) appeared single or double. Another response, that a single line appeared but was misaligned with the target, was possible and indicated that the view from one eye was being suppressed.

Threshold Conditions: Four thresholds were determined for each subject, one at each crossing of two disparity directions (positive and negative), with two viewing exposure times (100 msec and 3 sec).

Threshold Determination: Thresholds were determined with a maximally efficient threshold bracketing technique.

Results and Discussion

The main findings of this study are: (1) observers are relatively intolerant of negative disparity, (2) longer viewing is more likely to lead to a diplopia effect than very short glances, (3) resistance to disparity appears to be an individual trait, and (4) a large proportion of responses involve suppression of the view from one eye. The overall median negative disparity threshold was 1.2 mrad and the overall positive threshold was 2.6 mrad. These values are recommended as the maximum disparities acceptable for wide-field-of-view Canopy-HUD optical systems. Since the values are so small, we further recommend that the canopy and HUD be treated as a system, with technical interaction between the vendors, and between the vendors and the USAF. The disparity values indicate the net difference between both system components, so optimization may be possible by appropriately matching the optics.

Further details may be found in a forthcoming AFAMRL Technical Report by R. Warren, T. Connon, L. V. Genco, and H. L. Task.

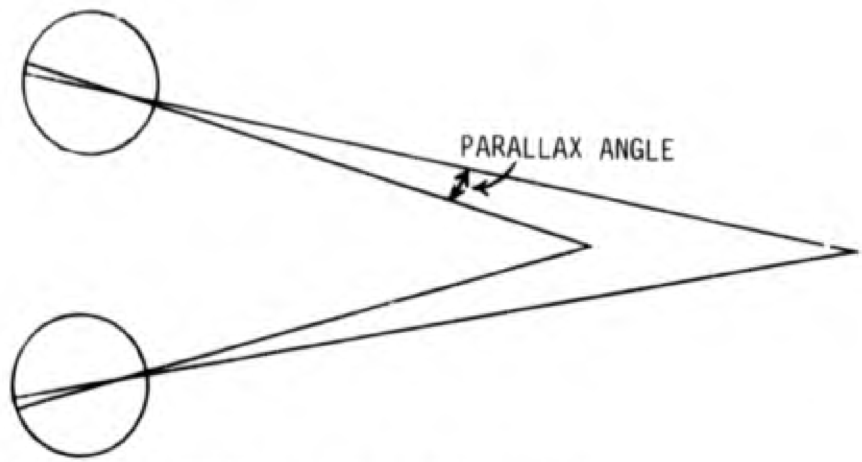

Figure 1. Parallax angle and stereopsis

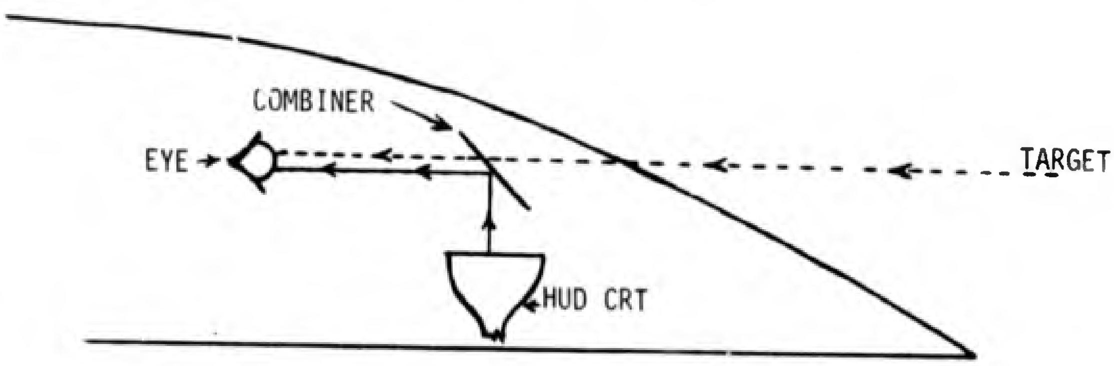

Figure 2 A. The canopy affects light from only the target. (side view)

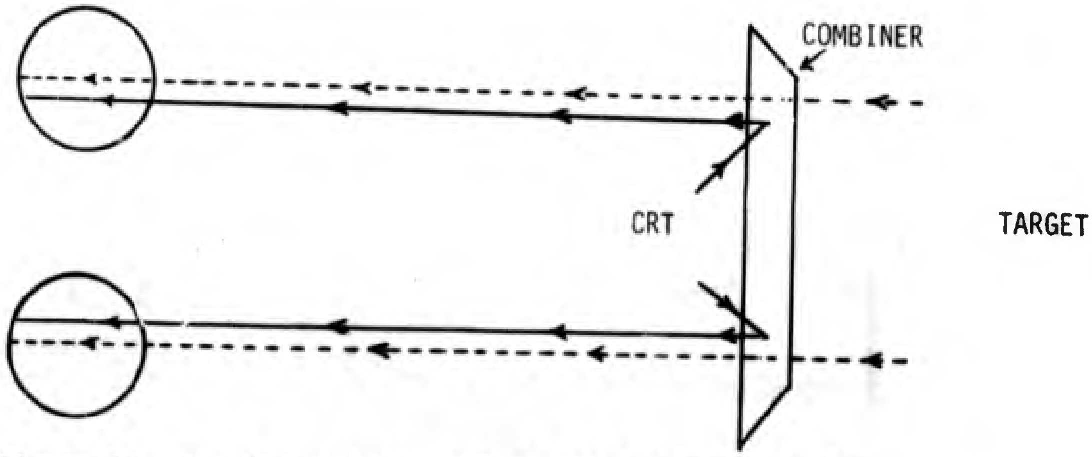

Figure 2B. The HUD combiner affects light from both the target and the CRT. (top view)