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THE EYES PREFER REAL IMAGES

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For better or worse, virtual imaging displays are with us in the form of narrow-angle combining-glass presentations, head-up displays (HUD), and head-mounted projections of wide-angle sensor-generated or computer-animated imagery (HMD). All of our military and civil aviation services and a large number of aerospace companies are involved in one way or another in a frantic competition to develop the best virtual imaging display system. The success or failure of major weapon systems hangs in the balance, and billions of dollars in potential business are at stake. Because of the degree to which our national defense is committed to the perfection of virtual imaging displays, a brief consideration of their status, an investigation and analysis of their problems, and a search for realistic alternatives are long overdue.

CURRENT STATUS

All of our currently operational tactical fighter aircraft are equipped with HUDs. Helicopters are navigated and controlled, and their weapons are delivered, with a variety of imaging displays including, in addition to HUDs, both panel-mounted and head-mounted image intensifiers and forward-looking infrared (FLIR) and low-light TV displays. Even some strategic aircraft and a few commercial airliners contain virtual imaging displays. A new generation of remotely piloted vehicles (RPV) are intended to be flown by reference to wide-angle but relatively low-resolution sensor imagery presented stereoscopically by head-mounted binocular displays. And Detroit is about to offer HUDs for cars.

THE TROUBLE WITH HUDS AND HMDS

As for the operational problems, about 30% of tactical pilots report that using a HUD tends to cause disorientation, especially when flying in and out of clouds (Barnette, 1976; Newman, 1980). Pilots frequently experience confusion in trying to maintain aircraft attitude by reference to the HUD's artificial horizon and "pitch-ladder" symbology, particularly at night and over water, and there are documented cases of airplanes becoming inverted without the pilots' awareness (Kehoe, 1985). Pilots have also reported a tendency to focus on the HUD combining glass instead of the outside real-world scene (Jarvi, 1981; Norton, 1981). The resulting myopia is a special case of the more general anomaly known as "instrument myopia" (Hennessy, 1975).

Misaccommodation of the Eyes

Whatever the cause, it is a repeatedly observed experimental fact that our eyes do not automatically focus at optical infinity when viewing collimated virtual images, but lapse inward toward their dark focus, or resting accommodation distance, at about arm's length on average (Hull, Gill, and

Roscoe, 1982; Iavecchia, Iavecchia, and Roscoe, 1988; Norman and Ehrlich, 1986; Randle, Roscoe, and Pettit, 1980). The perceptual consequence of positive misaccommodation is that the whole visual scene shrinks in apparent angular size. This shrunken appearance causes distant objects to be judged farther away than they are, and anything below the line of sight, such as the surface of the terrain or an airport runway, appears higher than it really is relative to the horizon (Roscoe, 1984, 1985).

The effect of the HUD optics is illustrated in figure 1. The experiment was conducted by Joyce and Helene Iavecchia at the Naval Air Development Center in Pennsylvania. A HUD was set up on one rooftop and a "scoreboard" assembly with selectively lighted numerals of various sizes was mounted on top of another building 182 m away and of about the same height. Observers were asked to read scoreboard numbers as they appeared and also numbers presented by the HUD on half the trials. Concurrently, the eye accommodation of the observers was measured with a polarized vernier optometer.

Figure 1 shows the average focal responses to the scoreboard numerals and the background terrain beyond the scoreboard, with the HUD turned Off and with it turned On. In either case the observers' focal responses were highly dependent on their individual dark focus distances; in fact, knowing each individual's dark focus accounted for 88% of the variance in focal responses under all conditions of the experiment. Excluding Observer 9, whose dark focus was almost three diopters (D) beyond infinity, the average for the remaining nine emmetropes was 1.06 D, or just short of 1 m.

But the striking result shown in figure 1 is the fact that when the HUD was turned On, for all 10 observers, focus shifted inward from an average of 0.02 D, or 50 m, to an average of 0.20 D, or 5 m. Once again excluding Observer 9, the average inward shift was from 0.27 D, about 4 m, to 0.47 D, about 2 m. Although such shifts have little effect on the apparent clarity of the visual scene, they have tremendous effects on the apparent size, distance, and angular direction of terrain features.

Accommodation and Apparent Size

Despite wide individual differences among observers, the average apparent size of objects is almost perfectly correlated ($r > 0.9$) with the distance at which the eyes are focused (Benel, 1979; Hull, Gill, and Roscoe, 1982; Iavecchia, Iavecchia, and Roscoe, 1983; Roscoe, Olzak, and Randle, 1976; Simonelli, 1979). Thus, the positive misaccommodation induced by collimated HUD symbology can partially account for the fact that pilots flying airplanes or flight simulators by reference to virtual imaging systems make fast approaches, round out high, and land long and hard (Campbell, McEachern, and Marg, 1955; Palmer and Cronn, 1973).

Such biased judgments also partially account for the fact that helicopter pilots flying with imaging displays frequently collide with trees and other surface objects and the fact that the U. S. Air Force between 1980 and 1985 lost 73 airplanes in clear weather because of pilot misorientation, resulting in controlled flight into the terrain (54), or disorientation resulting in loss of control (19) while flying by reference to collimated HUDs (Morphew, 1985). When flying by reference to panel-mounted or head-mounted imaging displays, helicopter pilots approach objects slowly and tentatively, and still they are frequently surprised when an apparently distant tree or rock suddenly fills the wide-angle sensor's entire field of view.

Fixed-wing airplane pilots flying with HUDs also judge a target to be farther away and the dive angle shallower than they are, resulting in almost-always-fatal "controlled-flight-into-the-terrain" accidents. In the U.S. Air Force, such accidents have continued to occur at the rate of about one per month since HUDs came into general use at the beginning of this decade. Two months ago (June 1987) an F-16 left a smoking hole in the ground, and last month it was an F-111. The Navy's experience has been essentially the same.

Optical Minification

Misorientation and disorientation with panel-mounted and some head-mounted imaging displays are exacerbated by the fact that limited display size and the need to display the widest practical outside visual angles typically result in drastic optical minification, which adds to the perceptual minification caused by the misaccommodation. If the display area were not so limited and could be varied to accommodate the wide individual differences in dark focus distances, images of the outside world could be magnified by appropriate amounts to neutralize each individual's perceptual bias. The average magnification required would be X1.25 (Roscoe, 1984; Roscoe, Hasler, and Dougherty, 1966), but this value would be correct for only a portion of the population, possibly requiring stricter pilot selection.

Image Quality

Display minification and perceptual biases are two sources of error in human judgments of size, distance, and angular location, but there are other sources of error as well, namely, the variable errors associated with adverse ambient viewing conditions (atmospheric attenuation and reduced illumination), the limited resolution of cameras and display devices, and the further loss of resolution with image intensification. All of these factors serve to reduce contrast and detail, the principal components of image quality, and the accuracy with which people can extract positions, rates, and accelerations relative to outside objects in the visual environment.

DISPLAY ALTERNATIVES

Because of the adverse effects of virtual images on eye accommodation, as well as the optical minification and poor image quality typically associated with sensor-generated displays, our judgments of spatial relations are simply not good enough to support complex flight missions as safely or effectively as we need. To date the advocates of virtual image displays have adamantly refused to acknowledge the implication of misaccommodation in the misorientation and disorientation of pilots flying with HUDs. Instead they have attributed the problems primarily to the limited fields of view afforded by the combining glasses used with current systems.

To address the limited-field-of-view problem, each of our military services, including the Marines, is spending millions of dollars a year—to say nothing of the IR&D funds invested by private companies—to develop wide-angle, head-mounted imaging displays, in many cases coupling camera line-of-sight to head or eye orientation. Still clinging to the assumption that the eyes will focus collimated images at optical infinity, the advocates of head-mounted displays and

head-coupled sensors now promise that a pilot will be able to maintain geographic orientation and make veridical judgments of distances, rates of closure, and angular directions to visible navigation points and targets.

To dispel any doubt that such promises will come true, designers of some sensor and display systems are delivering imagery from two cameras independently to the two eyes to provide stereoscopic viewing (or even hyperstereo by exaggerating the interocular distance between the cameras). Many are convinced that stereo viewing will create an illusion of "remote presence" and thereby improve judgments of size, distance, and angular location sufficiently to make it unnecessary to provide automatic sensors of vehicle positions and rates for navigation and obstacle avoidance. Experience with head-mounted displays, whether binocular or biocular (both eyes receiving the same images), does not warrant these wishful thoughts.

Evidence from a variety of experimental and operational contexts indicates that binocular judgments of size and distance are not markedly better than monocular judgments, except at very short distances (as in threading a needle). In fact, Holway and Boring (1941) found monocular size judgments to be more nearly veridical than binocular judgments when good distance cues are present. In any case, the large bias errors in size, distance, and angular position judgments caused by misaccommodation to virtual images would more than cancel any minor benefits of disparate images to the two eyes.

In the absence of some striking breakthrough in human genetic engineering, the long-range prognosis for head-mounted displays is not good. Not only do our eyes refuse to behave as display designers would like to believe, but the illusion ofvection induced by the "streaming" of objects near the periphery of wide-angle views often leads to motion sickness, particularly with head-coupled sensors and the consequent smearing of the images with head movements. Unfortunately our sole dependence on virtual imaging displays for tactical missions (HUDs now and HMDs in the future) has resulted in almost total suppression of research and development of more easily optimized direct-view displays of sufficient angular size to provide the needed fields of view with appropriate magnification.

WHAT CAN BE DONE

If we dismiss the genetic engineering approach, there are still several reasonable courses of action. In the short run, these include (1) trying to "fix" the HUD optics to compensate for the misaccommodation that leads to misorientation, and (2) modifying the ambiguous HUD symbology that leads to attitude reversals and subsequent disorientation. In the longer run, abandon the virtual image approach and concentrate on large, integrated forward-looking and downward-looking direct-view displays in which computer-animated flight attitude, guidance, and prediction symbology is superposed on sensor-generated real-world imagery.

Fixing the HUD

To induce pilots to focus at optical infinity when viewing virtual images, Norman and Ehrlich (1986) in Israel introduced a negative focal demand of -0.5 D with the desired result, although there were wide individual differences in responses as a function of individual dark-focus

distances. Thus, the first experimental fix should be the addition of variable optical refraction to offset each individual pilot's inward focal lapse induced by the HUD's virtual images. Turning the HUD On would require a key coded to select the pilot's specific correction based on the dark focus. At this time, no one can be sure how successful this fix will be, but it must be tried.

Almost as important is the complete redesign of HUD symbology. Just how complicated and confusing it is can be appreciated from the estimate of an Army Instructor Pilot that an average student helicopter pilot requires 200 hr of simulator and flight training to master the gaggle of symbols (personal communication). Furthermore, the attitude presentation in fixed-wing airplanes is conducive to horizon and pitch-ladder control reversals that result in disorientation and "graveyard spirals" at night and in marginal weather. At the very least, a frequency-separated predicted flightpath "airplane" symbol that banks and translates in immediate response and in the same direction as control inputs should replace the present velocity vector and acceleration symbology (Roscoe, 1980, Ch. 7; Roscoe and Jensen, 1981).

Presenting the Big Picture

If head-mounted, wide-angle imaging displays are ever to be safe and successful, the apparent minification of the outside world will have to be compensated for by individually selectable optical magnification, or the eyes will have to be induced to focus at or near optical infinity, as in the case of HUDs. Neither approach will be simple. Furthermore, the whole virtual image display concept depends on a gross reduction, rather than any increase, in the weight of any head-mounted device to be used in a high-G environment. All things considered, it is surely premature to give up on direct-view, panel-mounted displays.

Large, integrated, direct-view displays offer many advantages in terms of visual performance as well as ease of achievement and lower cost. Eyes focus real images more accurately than virtual images (Hull, Gill, and Roscoe, 1982; Iavecchia, Iavecchia, and Roscoe, 1988; Randle, Roscoe, and Pettit, 1980). Although many with 20/20 vision cannot focus out to optical infinity, all emmetropes can focus at the distance of cockpit instrument panels. Thus, although magnification of sensor-generated or computer-animated images of the outside world will be required, as it is with direct-view projection periscopes (Roscoe, 1984; Roscoe, Hasler, and Dougherty, 1966), a single, fixed-magnification factor of about X1.25 will suffice for most emmetropes.

To make room for large forward-looking and downward-looking (and possibly sideways-looking) displays, a lot of single-variable dedicated instruments and controls will have to be replaced by insets that appear selectively on the large displays as a function of the mission phase, aircraft configuration, mode of operation, weather and traffic, system malfunctions, and in the case of military aircraft, weapon selection. Furthermore, with the ever-increasing complexity of aircraft systems and military missions, many future airplanes—despite their high degrees of automation—will require at least two pilots with a redistribution of functions and available information.

In the military there will always be a heavy premium on being able to take advantage of whatever is visible to the naked eye. However, trying to combine synthetic imagery with contact visibility compromises both, and a strong case can be made for distributing operational functions and information sources between an "inside" pilot and an "outside" pilot. The inside pilot would normally do all the flying in instrument meteorological conditions (IMC) and most of the flying under visual meteorological conditions (VMC), using a direct-view, wide-angle projection periscope and

the large, panel-mounted pictorial displays surrounding the pilot deep inside the airplane. The outside pilot would use his or her eyes to supplement the imaging sensors, do most of the communicating and procedural housekeeping, and fly any maneuver that requires direct contact visibility.

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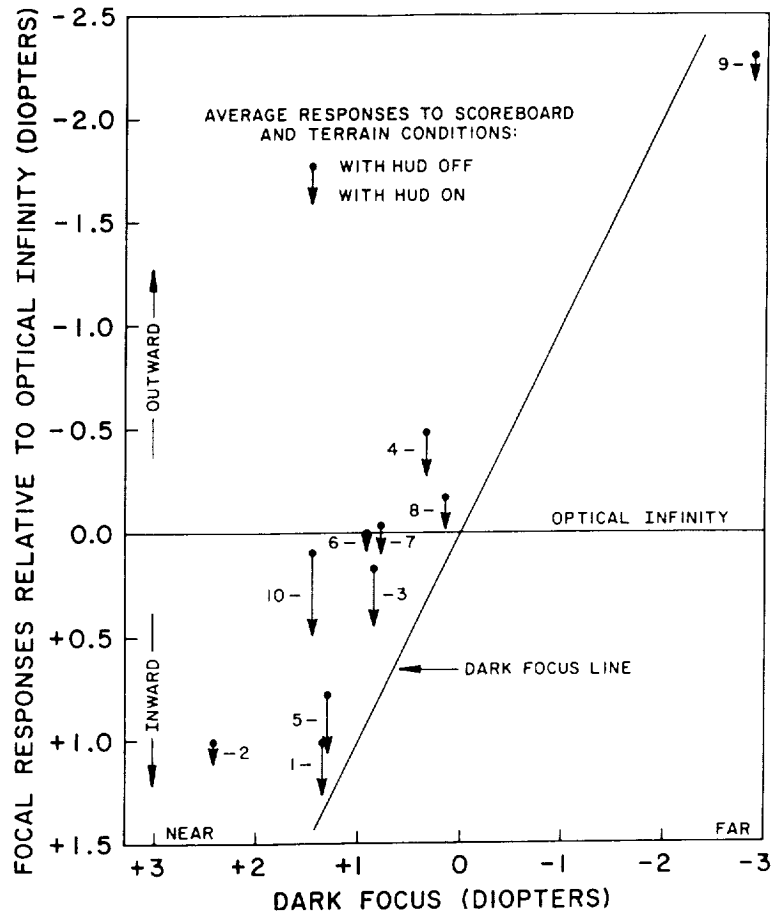


Figure 1.— Average focal responses to the scoreboard and the terrain conditions with HUD On and Off, plotted against each individual's dark focus.

