Optimized Visual Interfaces for Combat Pilots

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1. Introduction

In everyday life it is unlikely for us to find ourselves in situations of critical sensory overload. We generally live well within the envelope of our attentive capacity, except perhaps for entertainment. But fighter pilots in combat are overloaded as a matter of course. The cost of errors resulting from this overloading is often human lives and many millions of dollars of hardware. Therefore, any increase in the efficiency of the pilot interface is well worth it. One of the most productive uses to which knowledge of the human visual system can be put is optimizing this interface.

There is substantial evidence that the visual system contains numerous largely independent feature detectors that can be attended simultaneously. Experiments determine their degree of interdependence as well as the thresholds for feature detection and resolution. Knowing the capacity of each dimension of visual input and attention, interface designers can enhance data and present it in the most efficient manner for pilots to perceive it.

2. Pilot Interfaces

2.1 Situational Awareness

The key to pilot success is situational awareness. “Pilot error” is generally a loss of situational awareness (SA), which causes inappropriate actions given the true situation. Loss of SA costs money and lives in peacetime accidents and more so during the unrestrained conditions of war. The pilot must first be aware of his own bearing and status. This includes speed, orientation, flight path and flight envelope as well as the status of his equipment. He must also maintain awareness of threats and obstacles. These include enemy aircraft and missiles, ground obstacles, and other air obstacles like friendly aircraft. The history of aviation is a story of improvement to avionics and avionic interfaces, resulting in constant increases to pilot SA.

2.2 Interfaces

The state of the art in avionic interfaces is large, active-matrix, multi-function displays (MFDs) which replace the rows of gauges, instruments, and CRTs in older planes. Centralized display and control computers gather data from the numerous sources available to the pilot and allow for customized, optimal display of relevant information at each stage of a mission. For example, the status of a plane includes engine condition, fuel reserve, flap and control positions, radar mode, weapon status, radio and transponder settings, and numerous other details. Bearing includes orientation relative to the horizon, altitude, speed, direction, location, and flight paths. Avionic data comes from onboard sensors and computers, radar, the Global Positioning System, and even other planes and command centers. The pilot usually doesn't need to know where the information comes from, nor does he need to see all of it all the time. The computerized interpretation and optimization of the display of such data is key to decreasing the load on the pilot's limited attention.

2.3 Challenges

One of the constant challenges for the pilot is optimizing all of these parameters within the envelope of both his mission and his aircraft. In wartime, aircraft are usually maximally loaded while onboard fuel is minimized. This puts tight constraints on the altitude and speed through which the pilot can fly, and limits his maneuverability. Most of the parameters for efficient operating can be effectively computed, but the pilot must be made aware of them and the cost of exceeding them. For example, his load may constrain him to rolls of 7 Gs without risking damage to the plane, but if he is evading a surface-to-air missile (SAM), he needs to know that the plane is still mechanically capable of 12 G rolls if the alternative is losing it completely. An unexpected threat may prompt a change in the planned flight-path, which the pilot must perform without crossing the mission parameters of fuel consumption or time-on-target.

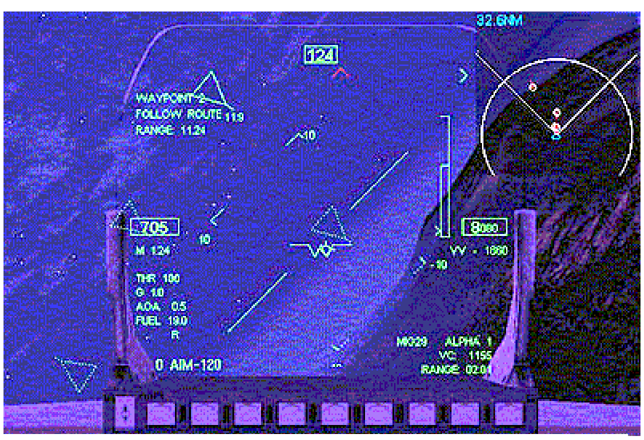
Enemy planes and SAMs require even more rapid and precise SA on the part of the pilot. Effective close-range engagement and evasion of these threats has conventionally depended on direct visual contact by the pilot. Most current systems display only the radar type, status, direction (in the horizontal plane), and rough distance of an active threat like a plane or missile. Head-up displays (HUDs) can give further information about relative location and bearing of these threats, but only within the limited field of view of the display. However, onboard sensors are generally able to collect and interpolate more data on these threats than is effectively shown through the HUD and MFDs.

Modern FA-18 cockpit with HUD and 3 MFDs.

Ground obstacles present just as grave a threat as enemy weapons. Low-level maneuvering is key to aerial tactics, but tends to be limited because it is so difficult and dangerous. It is notoriously hard for pilots to maintain a reliable perspective of their orientation and speed relative to the ground. Modern fighters are equipped with a LANTIRN (Low Altitude Navigation and Targeting Infrared for Night) radar and infrared sensor system for terrain following and target acquisition under darkness and weather. However, the pilot is currently only presented with a forward-looking infrared image via the HUD or MFD. Stereoscopic and peripheral cues would greatly enhance SA of the ground.

4 F-15s flying close formation.

Other air hazards include friendly aircraft. Aerial tactics necessitate very close formations and maneuvers. Mid-air collisions under these circumstances are also fundamentally a problem of SA. Under ideal conditions, the pilot can use peripheral vision to maintain formation and SA of very close aircraft. Visual interfaces should take advantage of this natural system, accentuating the position of airplanes via peripheral cues when visibility is suboptimal. Pilots are also prone to “friendly fire” accidents in combat because of the speed at which encounters unfold and the sheer number of aircraft that are present in a typical mission. There exist “Friend or Foe” systems to verify the identity of aircraft, but it is also necessary to communicate this data—or, more importantly, the lack thereof—through the tracking and targeting systems.



HUD from F-22 simulator. Inset is radar-mode MFD.

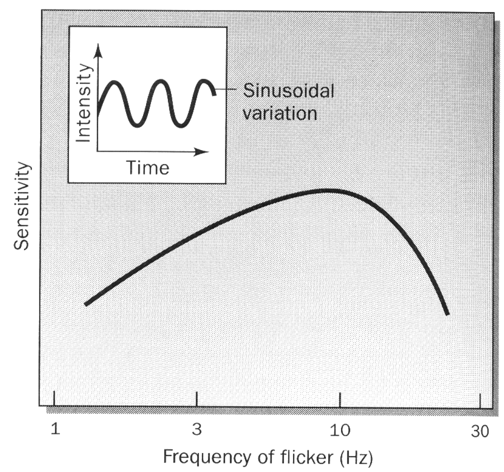
2.4 Interface Options

In addition to the current MFDs and HUDs, some ground-attack units have begun to use stereoscopic night-vision goggles to enhance SA at night and in weather. These take advantage of the binocular visual system. However, like the LANTIRN HUD system, they come up short because they are monochromatic and span a visual angle of no more than 40 degrees. The greatest shortcoming of current systems is that they generally do not make use of the binocular visual system or the retinal periphery to display information. Some helmet-mounted displays are under consideration that could change this by presenting color, stereoscopic images across the entire visual field. Even more exotic are virtual cockpits which eliminate the view of the outside, instead gathering all data through onboard sensors and surrounding the pilot in an optimized, computer-generated interface.

3. Optimizing the Visual Interface

The computerized interface with the pilot can be optimized in many dimensions. It should be tuned to the human visual system's response curves for such factors as flicker rate, frequency, orientation, closure, convexity, color, depth, motion, and attention. Since pilots are required to have flawless vision, interfaces can be tailored to the maximum thresholds of these features.

3.1 Flicker

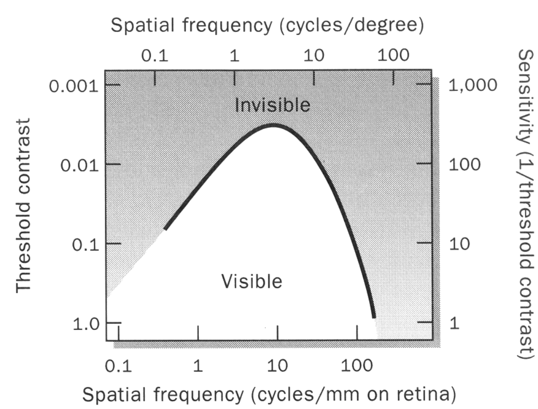


The threshold for the detection of a flickering stimulus varies by frequency and total change in intensity, as indicated in the figure (from Sekuler & Blake). Therefore, for a given intensity gradient, a flicker stimulus will be most perceptible at about 10 hertz. The most ostensible use of flicker is to attract attention to a point. It is possible that flicker stimuli effectively attract attention by stimulating both the retinal M cells (due to the rapid change in contrast) and P cells (if the flicker stimulus attains a high contrast with its surroundings), which project to the distinct magnocellular and parvocellular systems. Flicker rate could be modified depending on the severity of a threat or warning. For example, it would be natural to increase the flicker rate on the radar map of a locked enemy missile as it gets closer to the aircraft. In a situation in which he had to evade multiple missiles, this would be one cue to keep the pilot's attention on the most imminent threat.

I suspect that perception of flicker rate is largely independent of the other stimulus dimensions mentioned here, which would make it an especially useful cue for managing pilot attention. This should be verified experimentally. I would first conduct tests to see how overloading attention affects judgments of the rate of flicker of a stimulus. For example, have subjects search a field of colored letters at various orientations for a particular color at a particular orientation and read the letter, while simultaneously indicating which of various flickering stimuli is most rapid. This would suggest a threshold of discrimination for flicker stimuli under limited attention, which is essential if it is to be used as an attention cue to prioritize threats and warnings to the pilot. I would also verify the invariance of flicker rate across the visual field by collecting data from all areas. Basically, this could be done by mapping the response curve in the periphery, near-fovea, and fovea in both the upper and lower visual fields. The response curve is determined as the variance in intensity needed at each frequency for the subject to perceive flicker. Any disparities in response curves would have to be accounted for in visual interfaces, as would the damping of the intensity gradient in the upper visual field that results from the glare of the sun. In this manner, flicker rate could become both a very reliable attention cue and useful source of information.

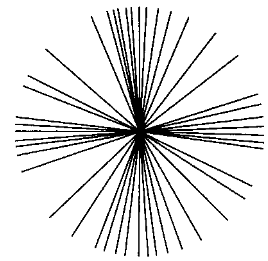
3.2 Frequency

The visual system has a varying sensitivity to different spatial frequencies. Sensitivity at a point can be measured as the minimum contrast needed to perceive a grating of a given frequency. This sensitivity curve is known as the contrast sensitivity function (CSF), and a typical measurement for the fovea is shown in the figure (from Sekular & Blake). Given this information, we can optimize the visibility of a given image for a particular distance and point in the visual field. Basically, this involves performing a spectral decomposition of the image and magnifying it to maximize its product with the CSF. More formally, first note that we can translate CSFs at the same point in the visual field $\bar{f}$ for different distances ρ and ρ' using the following geometric relation: $CSF_{(\rho',\bar{f})}(t) = CSF_{(\rho,\bar{f})}(t\,\rho'/\rho)$. So, given an image ***I*** with spectral decomposition ***F***[***I***], we want to maximize $\Phi(x) = \int F[I](t/x) \cdot CSF_{(\rho,\bar{f})}(t)dt$ for the magnification factor ***x***. This magnification gives the optimum visibility of the image at that point.



3.3 Orientation

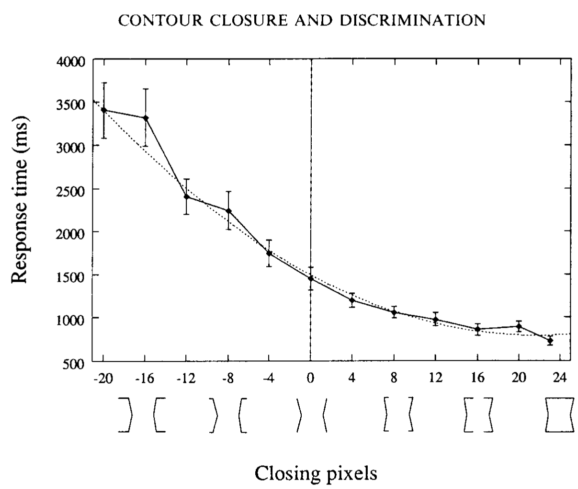
There is a bias in the orientation of cells in the visual cortex, as shown in the figure (from Sekular & Blake). A very disproportionate number of these cells are tuned to lines and edges that are nearly horizontal or vertical. This results in an "oblique effect" whereby non-normal edges are more difficult to perceive and resolve. Due to this effect, interface icons should try to maintain the property that under rotation they always have at least one edge that is nearly horizontal or vertical. For example, the HUD figure on page 3 shows triangular target indicators and an extended "W" icon in the center of the display that have this property. This effect can also be used to prioritize attention. For example, a diamond target indicator could slowly rotate to a square as the target approaches weapon range, making it more salient as it becomes more relevant.



Preferred orientations of cortical cells

3.4 Closure & Convexity

Elder and Zucker showed a substantial increase in attention and discrimination as the closure of an object increases (see figure). Icon closure should therefore be maintained in interfaces. It also servers as another factor that can be manipulated to regulate attention. For example, the closure of target or waypoint indicators could be varied with range, since rapid attention is not required for such distant features. Experiments should be done to determine whether decreasing closure of an icon in an interface reduces the interference with attention to other features and data. If so, this would be a very effective way of managing SA.



I suspect that convexity is similar to closure in its effect on attention and discrimination, where more convex icons are easier to perceive. Convexity could be functionally defined as the area of an icon divided by its boundary length. The definition should be verified experimentally along with response curve under attention overload.

3.5 Color

Color has its own independent detector in the visual system, and is currently underutilized in interfaces. It can be used to cue attention or to convey general information like status without requiring the pilot to devote attention to unnecessary details. However, as with other independent feature detectors, designers must beware of the possibility of illusory conjunctions during attention overload. This occurs because attention is required to correctly associate different features, and when it is not available they may be haphazardly combined. An example of something to avoid: If a single MFD mode has a flashing red indicator for an engine fire, some other sort of flashing yellow icon for an enemy plane, and a red indicator for a missile lock; a pilot under the stress of evading the enemy may conjoin the flashing yellow icon with a red lock warning to perceive a flashing red light which leads him to shut down an engine. If the enemy decides to shoot, he is in big trouble!

3.6 Depth

Current interfaces also do not take advantage of the substantial resources devoted in the visual system to perceiving binocular disparity. The MFDs and HUD are fixed at about 1 meter while the outside of the plane is far beyond the effective 7-meter range in which binocular disparity exists. Nonetheless, depth resolution is very precise, with a resolution of 1mm at a range of 1 meter! Furthermore, depth cues are perceived automatically from binocular disparity, so this dimension puts no further load on attention.

The application of depth cues to terrain and air obstacle enhancement would be a tremendous benefit, alleviating the need to fiddle with radar modes or read numbers in the HUD to determine the relative distance of multiple threats. By collecting this information from radar and redisplaying it within the usable range of binocular disparity, attention capacity would be substantially increased, along with SA. To effectively convey this data, experiments must be conducted to map horopters (shells of perceived equal distance) across the entire visual field. Previc suggests that vertical horopters curve inward substantially in the upper visual field.

3.7 Motion

Another substantial visual subsystem is devoted to the perception and tracking of motion. This should be experimentally mapped across the entire visual field to determine the minimum speed (in visual angle per second) required to perceive motion as a function of retinal eccentricity or the size and contrast of a stimulus. Also useful would be the response curve for perceiving a change in speed versus stimulus acceleration, and any biases in the direction of motion perception. An interface that correctly compensated for all of these factors could route substantial quantities of data through motion detectors.

Like depth cues, motion generally lies outside of useful areas of response curves. Given the speeds at which a modern fighter operates, things either move too quickly to be seen or else lie too far away to be perceptible at all. Therefore, radar and other data should be modified by the pilot interface to lie within the practical range of perception. Motion-enhanced data on terrain and air threats would greatly increase SA.

3.8 Attention

Attention for each dimension of the interface has a critical onset period before it is effectively attended. The interface must ensure that stimuli are shown unchanged for that critical period so that they are correctly perceived. Experiments should also be done under high attention loads to determine variances in these attention response curves.

4. Conclusion

It is unfortunate that the highest attention loads are often accompanied by the highest levels of physiological stress. It takes conscious effort to withstand the high-G maneuvers necessary for engagement, evasion, and low-level flight. Attentive and perceptive response curves need to be experimentally mapped at various G-loads to determine the effect of maneuvers on them as well. During high-G maneuvers, the pilot's life-support system pumps fluid around his legs and torso to offset the negative blood flow, while pure oxygen is forced into his lungs. The interface should also compensate, shifting images to lower spatial frequencies, boosting contrast, and perhaps eliminating nonessential information, thus making it easier for the pilot to maintain SA.

The role of the pilot interface is to enhance data so that all useful information lies in the peak of the response curves for all dimensions of perception. Optimizing interfaces in this way may seem expensive, but if even one aircraft is saved, it is easily worth it. The most modern fighter being purchased by the Air Force is the F-22, which costs $100 million per unit. A single pilot error can cause a crash, which usually destroys the entire plane. Therefore, even a small improvement in the interface that prevents one such error is worth $100 million!

5. References

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