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TOWARDS A PHYSIOLOGICALLY BASED HUD SYMBOLOGY

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New concepts in HUD symbology, based on an understanding of the physiological mechanisms and ecological origins of the human visual system are described which may enable future HUD displays to serve as primary flight directors in addition to their current roles. The four key elements of this new symbology are: a) prioritization of space according to the three-dimensional structure of visual attention, b) an attitude display in the form of a global percept; c) effective preattentive attitude cueing based on an ecologically valid simulation of the visual terrain during flight; and d) visual reference framing which depicts the roll of the aircraft relative to a stable horizon. Prototypes which illustrate the "physiological HUD" concept are presented. The specific advantage of the proposed symbology may be to allow the pilot to maintain effective attitude control while directing his attention towards the out-the-window environment.

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TOWARDS A PHYSIOLOGICALLY BASED HUD SYMBOLOGY

INTRODUCTION

Perhaps the most important piece of avionics in the modern fighter aircraft is the head-up display (HUD). It also remains one of the most controversial of all cockpit instruments, as evidenced by a recent series of papers (1-4) and a recent symposium workshop (*). Despite its important role in allowing the pilot to focus on the out-the-window (OTW) environment, the current HUD clearly possesses major disadvantages in terms of the quality of its information presentation (especially in its attitude symbology), its compatibility with head-down displays, and its training costs. Should the HUD become a primary flight display as envisioned, it is doubtful whether current symbologies or even slightly modified ones will prove capable of serving the needs of a primary flight director and the needs of an OTW target-acquisition and weapons-delivery system. Accordingly, the intent of this paper is to stimulate new HUD design concepts based on an understanding of the physiological mechanisms and the ecological origins of visual attention and perception in humans. Given the remarkable three-dimensional capabilities of low-cost computer graphics systems, it is clear that the greatest limitation in the development of a new HUD symbology is no longer computational capability, but rather conceptual creativity.

The essential requirement of future HUDs will be to improve their delivery of primary flight information while retaining a "see-through" quality. The primary obstacles to this goal are a) limited total display area, b) excess cluttering of the limited space available, preventing an adequate "see-through" capability and OTW attentional focus, and c) reliance on a monochrome display, limiting the amount of potential cueing available to the pilot. Given that a) and probably c) will remain in the HUD displays of the immediate future, the means of avoiding further clutter to an already saturated display may require a break with previous symbology concepts towards a realignment that efficiently exploits the natural perceptual strengths of the human visual system. In particular, the ideal HUD symbology must a) be consistent with the three-dimensional structure of human visual attention, so that HUD space can be properly prioritized to direct pilots' attentional resources toward "far" vision to the maximum extent possible; b) exploit the global perceptual capabilities of the human visual system to spare valuable focal attentional resources yet maintain the "see-through" aspect of the HUD; c) create an ecologically valid symbology which effectively simulates those preattentive visual cues which are used in figure-ground segregation during everyday locomotion and object scanning; and d) apply the proper frame of reference of the movement of the aircraft in relation to the visual horizon.

The following sections will briefly outline various aspects of human visual attention and perception as they pertain to the above issues. Prototype

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* Aircraft Attitude Awareness Workshop, Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio, 8-10 Oct 1985

displays based on an understanding of the physiological and ecological basis of visual perception will illustrate the potential of a physiologically based symbology in accomplishing the goals of the future HUD.

THE STRUCTURE OF VISUAL ATTENTION

During the past two decades, it has been established that visual attention consists of two basic forms: spatial attention (5) and object attention (6). Spatial attention refers to the manner in which we attend to different regions of visual space, while object attention refers to the manner in which we attend to different features of an object that distinguish it from the visual background or other objects.

In the frontal plane, the visual quadrant represents the key module in the structure of spatial attention. For example, it has been shown that the "spotlight" of visual attention diminishes markedly when one crosses the horizontal and vertical meridians (7). Thus, the first rule in maximizing two-dimensional visual display efficiency is to arrange information in a quadrant format, so that all information in a particular quadrant can be taken in during a single "attentional glance". This concept requires that most if not all information in that quadrant should be related to the same basic function (e.g., altitude information).

Recent findings suggest that spatial attention may also possess a third dimension, involving "near" and "far" visual space. For instance, when we attend to far visual space (as pilots typically do), information in near vision is less easily perceived (8). The distinction between "far" vs. "near" visual attention should not be confused with "far" vs. "near" optical focus, although the two are normally related (i.e., we usually attend to that region of space upon which our eyes are focused). This distinction is important because we can also focus on one region of space while attending to another (e.g., fixating on an object while attending to the motion of our hand reaching for it).

The division of attention into "far" and "near" space appears to have evolved in primates (9), and may not be independent of the other two dimensions. When attending to extrapersonal visual space, for instance, our attention is actually biased towards the upper and right hemifields (9). In part, the upper field bias for far visual attention stems from the fact that objects in personal visual space generally appear in the <u>lower</u> visual field. It also relates to the fact that, in most individuals, the brain areas processing visual information from the upper right quadrant of the visual field possess specialized mechanisms for perceiving the more detailed images associated with far vision (9). This feature of our visual system strongly implies that the most important alphanumeric information on the HUD display (i.e., altimeter readings) should be placed in its upper right quadrant, since the pilot will ideally be attending to the distant OTW environment when viewing the HUD. As discussed in a recent theoretical review (9), the three-dimensional structure of visual attention presumably resembles the model shown in Figure 1. A prototype prioritization of HUD visual space, based on this hypothetical structure as well as the relative importance of various types of flight information, is shown in Figure 2. It should be noted that this arrangement is similar to that of many traditional "T" displays, but differs

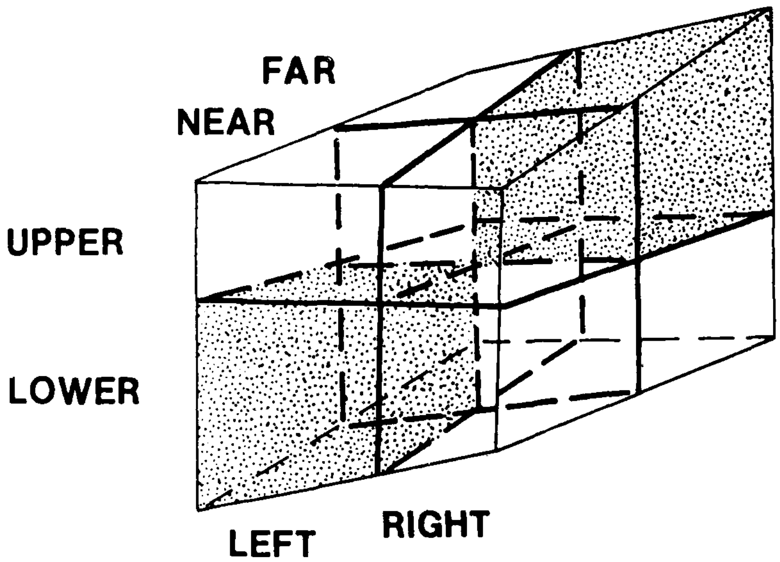

Figure 1. Hypothetical three-dimensional model of visual attention. In most individuals, the "far" attentional system is biased towards the upper and right hemifields, while the "near" attentional system is biased towards the lower and left hemifields. The most important quadrant for far vision is the upper right stippled area, while the lower left one is most important for near vision.

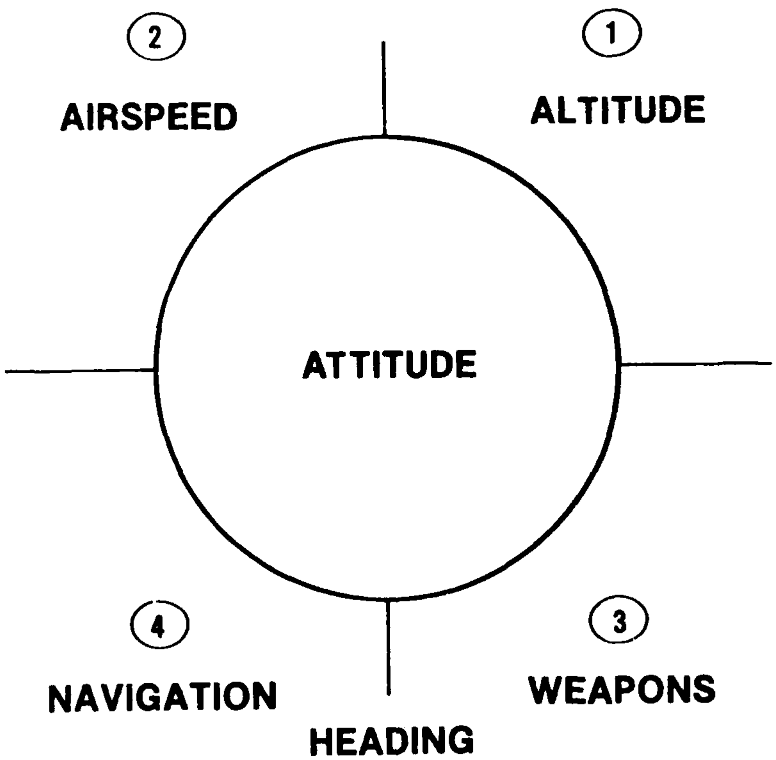

Figure 2. Prioritization of HUD space based on the three-dimensional structure of visual attention. Since far vision is biased towards the upper and right hemifields (9), the theoretically most desirable locations on the HUD during sustained out-the-window focus are as numbered. Functions contained in each quadrant are related to their crosscheck importance.

from most current HUDs in that no crossing of the vertical meridian is required to process altitude and airspeed data.

A major problem from the standpoint of display design is how to sustain the pilot's attention on the far visual environment while still allowing him to maintain proper spatial orientation. Ordinarily, spatial orientation is achieved using inputs from both the visual and vestibular systems, but pilots must learn to depend more on visual orientation information since vestibular inputs in the abnormal acceleratory environment of flight are frequently non-veridical (10). The mode of visual processing used in maintaining spatial orientation is referred to as "ambient" vision (11), and is generally believed to take place over the entire visual field, without recourse to large attentional resources. Under normal circumstances, we employ our peripheral visual capabilities to maintain proper orientation while reserving our focal attentional resources for foveal vision, where contour and color analysis are best performed. Unfortunately, the relatively small HUD field-of-view precludes the use of peripheral vision to maintain visual orientation ambiently. However, since one of the brain areas predominantly involved in ambient vision--the posterior parietal cortex (12)--is also linked to lower-field, near-vision functions (9), it may be possible to devise alternative means of maintaining ambient spatial orientation while the pilot's focal attentional resources are directed towards far visual space.

Thus, one of the major challenges for a well-designed physiological HUD display would be to allow the pilot to devote his focal attentional resources to far vision and to information which requires focal processing (such as digital altimeter readings) while ensuring that spatial orientation (i.e, attitude control) be performed in the ambient, near-vision realm. Fortunately, this task is actually quite similar to those performed during such everyday activities as reaching for objects and locomotion. During reaching, for instance, the eyes are fixated on the more distant object while the hand is almost effortlessly guided to it from the proximal lower visual field. It has been hypothesized that global perceptual capabilities in near vision developed to facilitate this guidance (9), and it may be possible to utilize such specialized mechanisms in maintaining spatial orientation with the HUD. Likewise, specialized lower-field ambient mechanisms may assist in figure-ground segregation and optical flow analysis during locomotion through the visual environment (13,14). These mechanisms allow us to trespass over uneven terrain and avoid obstacles in our path without even being consciously aware of them.

In summary, an analysis of the 3-D structure of visual attention suggests that, in addition to the adoption of a quadrant layout, two effective ways to maintain spatial orientation while releasing focal attention for far vision would be to a) exercise the global perceptual capabilities of our near-vision attentional system, and b) utilize those cues which contribute to preattentive figure-ground segregation and related functions. The following two sections will focus more directly on the role of global perceptual and preattentive cueing in HUD symbology design.

GLOBAL FORM PERCEPTION

In this section, an outline of global form perception as it is carried out by the human visual system is presented. The importance of this mode of processing for future HUD designs lies not only in its association with near vision (thereby freeing up focal perceptual resources for far vision), but also in its ability to create vivid percepts which are minimally dependent on actual contour information (thereby resulting in reduced display clutter and enhanced "see-through" visibility). The general benefits of HUD symbologies capable of exploiting the global perceptual capabilities of the human visual system have been alluded to previously (15).

Investigations into the nature of global perceptual processes date back to the Gestalt theorists of the early 1900's, although the past two decades have witnessed a tremendous expansion in our knowledge of them (16-19). Briefly, "global" form perception differs from "local" form perception in that it is more spatially distributed and less dependent on local contour detection. Because of this difference, global processes can tolerate a much greater amount of defocus, diplopia, and other types of visual degradation. Much perceptual and physiological evidence links global form perception to near vision, and it has been theorized that one of the major functions of global form perception is to perceive the movement of the hand in the near lower field while reaching for more distant objects (9). In this situation, the image of the fixated object in extrapersonal space is focused and stationary while the image of the rapidly moving hand is defocused and degraded. Although the HUD environment is different from an optical standpoint (i.e., the display itself is perceived as much closer to the optical distance of the outside world, thereby reducing the amount of diplopia and defocus), it does resemble the reaching situation from an attentional perspective in that focal attention must typically be directed OTW while global (ambient) processing is free to be utilized more proximally in maintaining spatial orientation (attitude) control. One of the most interesting lines of visual research during the past two decades has involved the study of illusory contours, a classic example of global form perception. As shown in Figures 3a and 3b, illusory contours are perceived through perceptual interpolations and correlations rather than point-to-point correspondences. As with other global form processes, motion enhances these percepts in a rather dramatic way, especially with large texture elements (Figure 3b). This is because global form perception is largely mediated by transient, low-spatial frequency channels in the visual system (9,20,21), presumably because of the large and rapidly moving image of the hand during reaching. As with low-frequency gratings, global forms are generally perceived more readily than are local forms (17), despite the fact that they are not defined by a continuous contour.

The use of global perceptual symbologies may permit a global construct of the head-down attitude indicator (AI)--whose superiority over the current HUD attitude format has been convincingly demonstrated (22-24)--to be integrated with the pitch-ladder format of current HUDs. A prototype of such a global attitude display is shown in Figure 4a. In addition to its see-through quality and its potential to exploit ambient, near-vision perceptual resources, this display offers several advantages over the current HUD attitude format (Figure 4b). The additional benefits include:

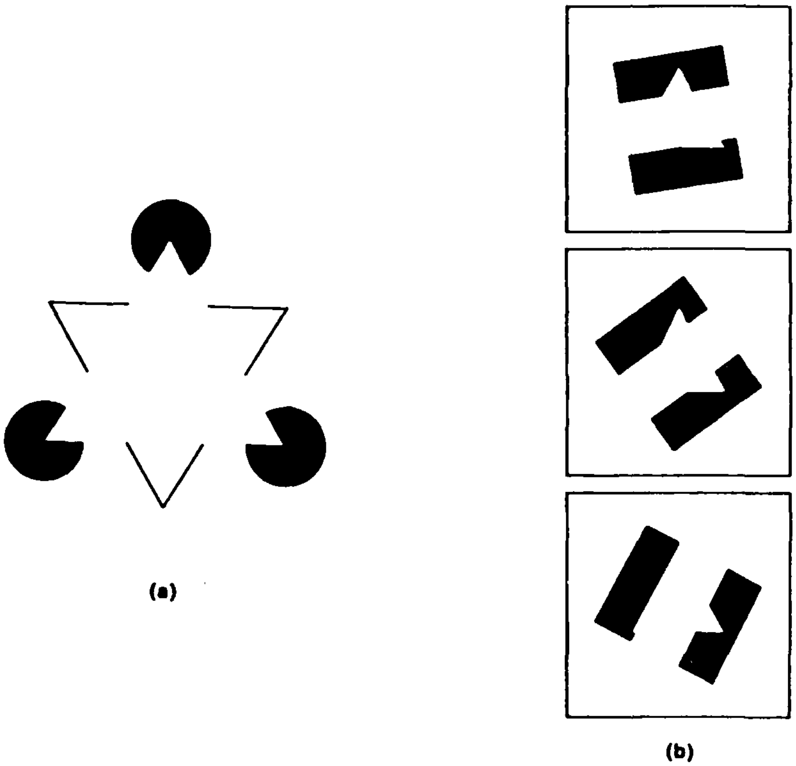

Figure 3. Two types of illusory contours: (a) stationary; (b) moving.

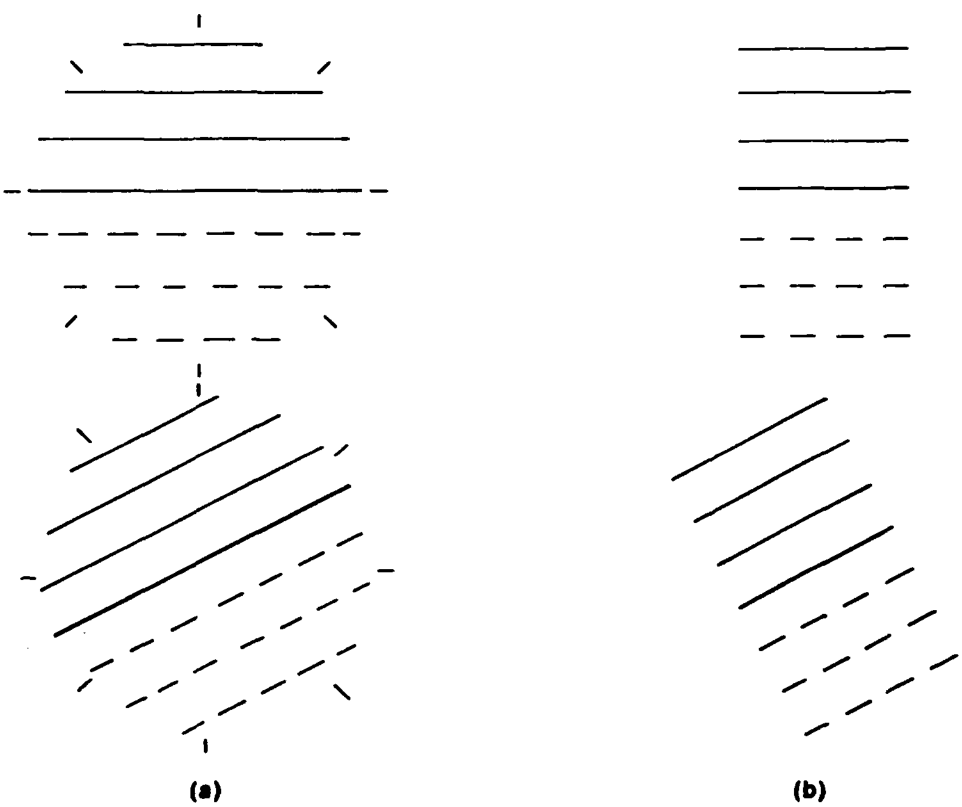

Figure 4. Comparison between (a) a HUD pitch ladder in the form of a global percept, and (b) the current HUD format, in both wings-level (top) and banked (bottom) aircraft attitudes.

- its similar shape to head-down AIs and prototype flat-panel attitude displays that may eventually be placed near the HUD,

- its capability of being perceived under degraded visual conditions (e.g., glare, flashblindness, cloud and ground masking), since global perception and other correlational and ambient-type perceptual processes tolerate more image degradation than does local form perception (9,11,16,18,20,25),

- its overall stabilization in a set position on the display, eliminating the obstruction of other critical information during slewing of the pitch scale, and

- its integration of precise pitch and roll information in a unified display, thereby freeing the pilot from the need to constantly switch his focal attention among the pitch ladder, sky-pointer, and bank scale.

In the context of pitch and roll scales, another important and somewhat counter-intuitive property of many global percepts--namely, their remarkable precision--should be noted. It has been shown, for instance, that in vertical alignment and related tasks in which the individual elements are widely spaced, global perceptual performance exhibits a precision which actually surpasses the spatial resolution of the fovea (25). Thus, global perceptual cueing, if utilized properly, offers the possibility of eliminating the myriad and redundant use of fine lines and digits on current HUD displays without a concomitant loss of precise aircraft control.

In summary, the presentation of the central attitude display as a global percept may represent a potentially major improvement over current HUD attitude symbology, at little or no cost in terms of display clutter. As with other symbologies, the precise size and form of the global display may have to vary somewhat during specific flight modes (e.g., weapon delivery, landing, etc.) to achieve a maximum versatility in performance. From the standpoint of "naturalness", a global attitude indicator should be ideal, since the effectiveness of global percepts is generally related to the extent to which they simulate "natural" percepts. For example, a particular global motion pattern is more likely to be detected if it has occurred in our previous perceptual experience (19). Indeed, it is doubtful whether a purely abstract set of computational algorithms could ever approach the remarkable global perceptual achievements of the human visual system, even given the impressive neural architecture of visual cortex.

PREATTENTIVE FORM PERCEPTION AND ITS ECOLOGICAL BASIS

Powerful preattentive perceptual mechanisms exist in the human visual system that assist in the segmentation of objects from the background scene during locomotion and object search. Indeed, the ability to engage in other endeavors (e.g., thought or conversation) while walking, driving a car, or searching for objects, clearly demonstrates how few attentional resources are necessary for such behaviors. Perhaps even more so than global perception, preattentive form perception bears an intimate connection with the ecological principles governing our interaction with the everyday visual environment. Thus, it may be argued that a well-designed HUD display requiring minimal focal attentional resources will ensure that orientation control is performed in a manner consistent with the ecological basis of human visual perception.

The ecological view of visual perception was emphasized by Gibson (13), who argued that the natural visual world provides a rich source of powerful and invariant information regarding the position and movement of objects (including ourselves) through the visual environment. Included among such natural cues are perspective, size and texture gradients, kinetic occlusion, and optical flow. It was the original intent of the AI to serve as a porthole to the outside visual world (26), but the physical constraints of the gyro display prevented many natural cues from being incorporated. Although it will be shown later in this section how a totally veridical representation of the outside world is inherently impossible for a HUD (or any other) attitude display, it will also be demonstrated how current computer graphics techniques may permit the delivery of several cues that dramatically expand the pilot's preattentive perceptual processing.

Preattentive cues generally include those which a) define an object's position relative to other elements of a scene (e.g., location, motion shear, color, size), or b) distinguish that object from other objects (e.g., color, size, shape). Experiments in visual object attention indicate that the selection of objects on the basis of their features is performed rapidly, preattentively and in parallel, whereas the combining of features into precise forms during a subsequent feature-integration stage requires focal attention (6). It has also been shown that color, followed by size and shape, is the most powerful of the object cues (27), although none of these cues is as effective as a prior knowledge of the stimulus' location. However, certain motion flow discontinuities (e.g., shearing motion) may be even more salient than color in segregating elements of a scene (28), especially under those degraded visual conditions in which our motion sensitivity exceeds our static form-detection capability (11).

Unfortunately, the location cue has limited usefulness in sky-ground demarcation because the relative position of the attitude display's horizon is always changing as a consequence of the movement of the aircraft. Nor is color likely to become available on HUD displays of the immediate future. Motion flow may be useful in select instances, but totally realistic simulations of terrain flow in attitude displays would compromise the ability of the HUD to deliver precise pitch information, as will be discussed later. It is important, therefore, that the remaining cues (i.e., size and shape) be effectively utilized for visual orientation control. Figure 5 shows how effectively size cueing promotes figure-ground segregation, when it is defined both in terms of thickness (Figure 5a) and line length (Figure 5b).

Current HUD pitch scales do not utilize size differences for discriminating sky-from-ground, although such cueing has been proposed by others (24). Although shape is generally not as good as size, it can also be beneficial when used properly. For instance, the discrimination of broken from dashed lines in current HUD pitch scales can in most cases be performed preattentively, although under extreme visual blur conditions (e.g., during high-speed aircraft roll) individual segments in a broken line may smear together and lead to the perception of a solid line. On the other hand, the discrimination of rotated L's from upright ones cannot be performed preattentively for 180-deg rotations (Figure 6a), but can be for 90-deg rotations (Figure 6b). Surprisingly, the

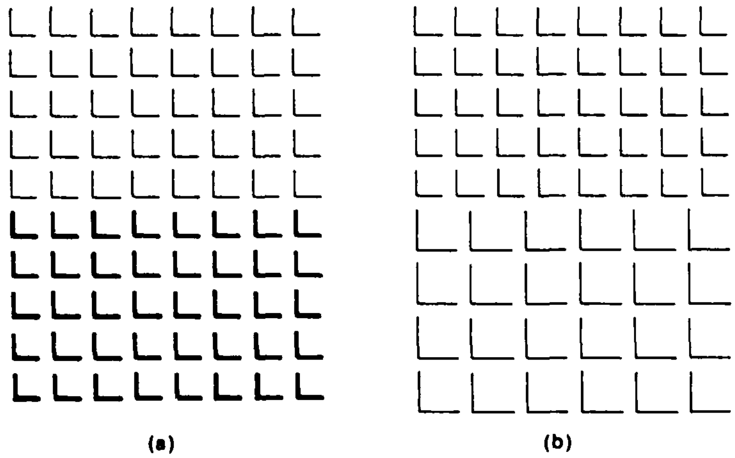

Figure 5. Effectiveness of size cues in preattentive form perception: (a) thickness, and (b) length.

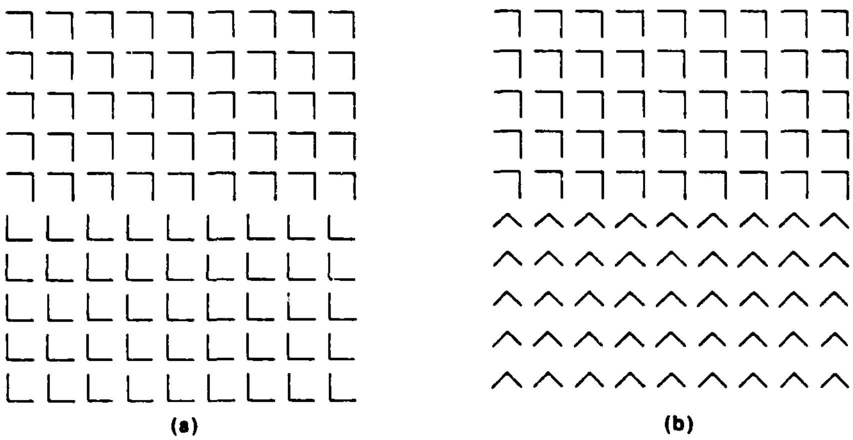

Figure 6. Comparison of elementary form segregation using (a) upright vs. rotated, and (b) upright vs. inverted discriminations.

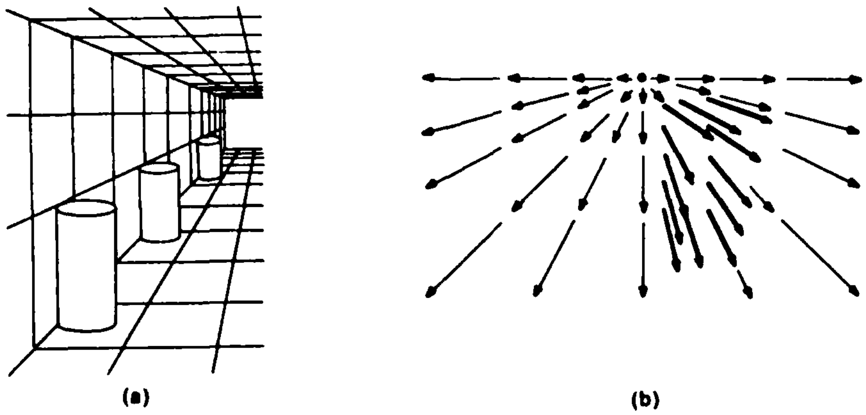

Figure 7. Illustration of two types of ecological figure-ground discriminations: (a) stationary figure/stationary ground, and (b) moving figure/moving ground, as in forward locomotion. Figure 7a is adapted from Gibson (29).

discrimination of 180-degree inverted symbols is required by the positive and negative pitch-scale formats of most current HUDs.

It appears that the effectiveness of various preattentive cues may relate to their ecological validity, particularly as they are used in figure-ground segmentation during locomotion. For example, nearer objects differ in both size, shape (perspectival slant), and magnitude and direction of linear optical flow from those in the visual background (see Figures 7a and 7b). Thus, discrimination of vertical vs. diagonal lines aids in figure-ground segregation, whereas upright vs. inverted line discriminations do not. Likewise, discrimination of opposite rotational movement is much harder than discrimination of motion shear (30), which more effectively simulates the relative translation of objects during natural locomotion. On the other hand, cues such as color may be more related to object attention and may have acquired their salience during the emergence of fruit-eating and fruit-searching in primates (9). In this context, it is worth noting that recent theories of primate vision have distinguished between the motion and color/form pathways in the brain (9,31). Accordingly, the salience of various preattentive cues may correspond to the properties of neurons located in early segments of these two pathways. For instance, shearing motion is effective for stimulating cells in middle temporal (MT) visual cortex (32), part of the "motion" system, whereas color is a salient cue for many cells in V4 (33), linked to the "form" system.

The link between preattentive cueing and ecological perception implies that a HUD attitude symbology which ideally simulates the actual terrain movement during flight will inevitably result in good preattentive cueing. Thus, future HUD symbologies should utilize not only perspective, size and texture gradients, and motion flow, but also such natural features as mountainous contours on the horizon and simulated landing strips during descent portions of the mission. The three-dimensional richness of "natural" attitude displays (see Figures 8a-d) would even make possible preattentive (albeit gross) estimations of altitude and airspeed, and would extend the HUD's role to specialized situations such as the vertical descent during Harrier landings (where the rate of optical expansion, or "looming", could reflect altitude and/or descent velocity).

Unfortunately, the other purposes of the HUD attitude display require that certain compromises be made in substituting "HUD ground" for "true ground". For instance, size gradients are limited because overly expanded pitch lines would result in an unacceptable occlusion of the display. Also, pitch lines must be equally spaced in order to be "conformal" to the outside world, thereby precluding a veridical depiction of texture gradients. Fortunately, size and horizontal spacing gradients by themselves appear to effectively simulate the natural gradients in our ecological visual representation. Finally, the pitch lines on the attitude display must remain stationary in a constant-pitch attitude, so they cannot truly depict the optical flow of the terrain underneath the plane. However, a global percept capable of crudely simulating actual motion flow is achievable using the technique of luminance "sweeping", which involves the progressive shift of a brief luminance increment across a stationary two-dimensional image.

It must be conceded that even an ecologically valid attitude display may still not address all of the reputed "unnaturalness" of current HUD displays. For example, information on currently mandated moving-tape altitude and air-

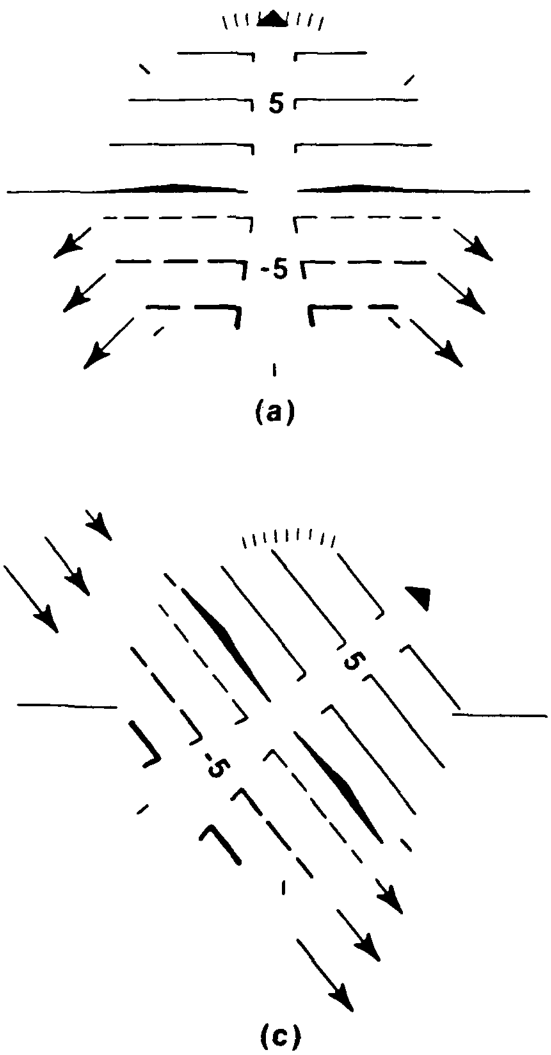

Figure 8. Global HUD attitude display employing a three-dimensional, ecological cueing structure, in four aircraft orientations: (a) wings-level flight/high-altitude; (b) wings-level flight/low-altitude; (c) level 45-deg turn; and (d) 15-deg nose-down attitude. Arrows denote approximate directions of motion flow.

speed scales may be difficult to process, but an understanding of ecological visual perception may be of limited relevance in refining or revamping such scales. It must also be conceded that many HUD tasks cannot be performed preattentively and in parallel, including those requiring identification of letters or digits, or fine orientation discriminations. Still, it would be advisable in these cases to present only one digital or fine analog readout per HUD quadrant to maximize the efficiency of the pilot's focal attentional resources. Also, displays which require focal attentional switching to perform two related tasks (e.g., pitch and bank control) needlessly distract the pilot from directing his focal attention in the critical OTW direction.

In summary, an analysis of the role of preattentive cueing indicates that certain HUD symbologies will allow the pilot to sustain his focal attention on the OTW environment while maintaining good spatial orientation preattentively. Generally, the effectiveness of various preattentive cues relates to their ecological relevance, so that a realistic simulation of the outside visual world will almost assuredly facilitate good preattentive processing. Like the global AI percept described in the preceding section, preattentive cueing in the "physiological HUD" will lead to a futuristic display which nevertheless blends in a very traditional attitude display concept.

SPATIAL ORIENTATION AND THE VISUAL FRAME OF REFERENCE

One of the long-standing issues in attitude display design concerns the proper visual frame of reference (34). Specifically, should the aircraft be portrayed as being stable while the visual background moves (simulating actual retinal image motion) or should the aircraft be portrayed as moving against a stationary visual background (as better fits our perceptual experience)? This distinction is illustrated in Figure 9, as applied to the case of aircraft roll motion. Although the inside-out perspective has been universally deployed in modern aircraft, it has also been shown to be the source of much confusion in both laboratory studies (34,35) and early pilot training (Ercoline, personal communication), thereby suggesting that it is much more confusing than alternate reference frames.

The fact that the world appears stable to us during head and body movements has generated a great deal of theoretical speculation dating at least as far back as Helmholtz in the late 1800's. Most researchers have postulated that a corollary discharge signal generated extraretinally instructs our perceptual system to ignore the retinal motion generated by egocentric movements, thereby stabilizing our perceptual world. The source of the extraretinal signal is not entirely known, but a recent review concluded that at least some of it must have a central (brain) origin (36).

The precise extent of extraretinal stabilization may depend on the relative weighting given to visual vs. other types of inputs in perceiving self-motion. Specifically, the degree to which retinal motion is relied on for perceiving self-motion seems to be inversely related to the strength of the corresponding vestibular percept, the most important extraretinal source of spatial orientation information. Accordingly, the HUD display should reflect this relationship by using visual background motion to code changes in aircraft attitude in those situations normally emphasizing retinal inputs, and using

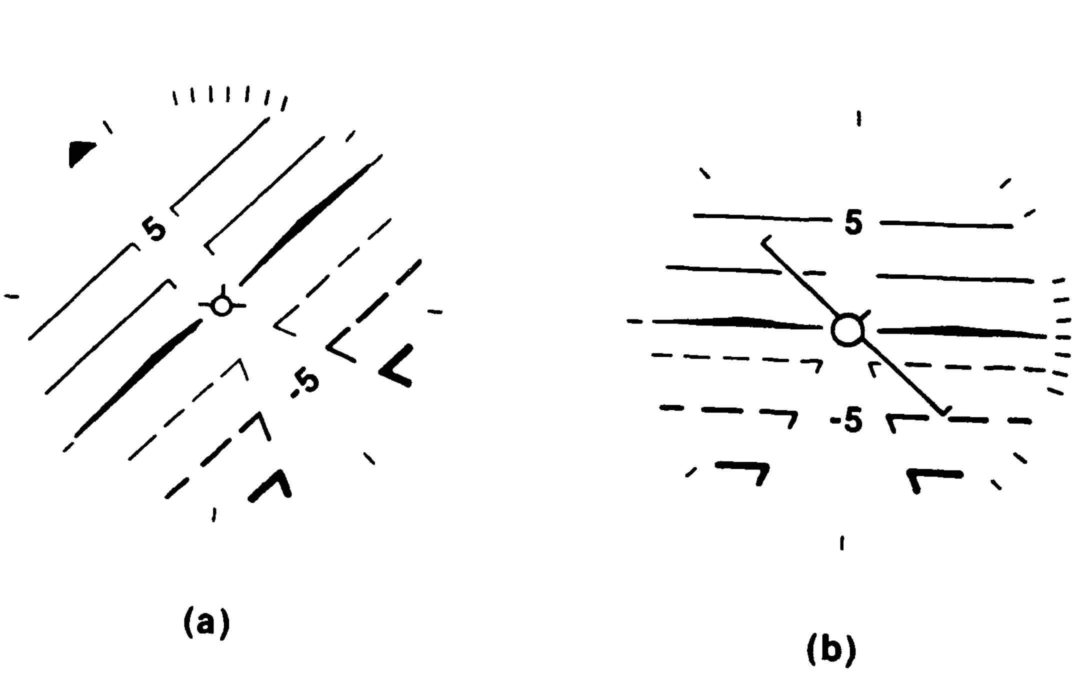

Figure 9. Illustration of the difference between a) an "inside-out" frame of reference, and b) a modified "inside-out" display in which roll is depicted using a moving aircraft symbol against a stable horizon.

aircraft symbol motion in those instances in which we rely more on our vestibular sense.

One application of this concept led to a "kinalog" display in which high-frequency motion (better sensed by the vestibular system) was coded by moving the object against the background display, whereas low-frequency motion better sensed by the visual system) was coded by movement of the background scene behind a stationary aircraft symbol (37). A somewhat less confusing situation involves the use of different frames of reference in different axes of motion. For example, visual scene motion much more powerfully induces a self-motion percept in the yaw and pitch axes than in the roll axis (38), whereas, conversely, the sensitivity of the vestibular system is apparently greater in roll than in pitch (39,40). Indeed, the important role of the visual field in stabilizing our perceptual world in the horizontal (yaw) and vertical (pitch) dimensions leads to a certain ambiguity concerning the motion of a stationary object against a moving background along these axes. For example, fixation upon a static dot surrounded by a moving background field can lead to the illusion that the dot itself is moving in the opposite direction (41), as can easily be demonstrated by observing the moon in the midst of rapidly moving clouds.

The above analysis suggests, therefore, that it may be more important to depict a stationary horizon and scene during roll motion than during pitch motion. Such a relationship was adopted by the Crane Flitegage display (10), one of the earliest attitude displays; and at least one study has demonstrated a greater advantage of outside-in displays in the roll vs. pitch plane (35). In addition to any theoretical or empirical justification, a major practical consideration favors the use of the "split-frame" perspective in future HUD displays. This consideration involves the fact that a 20-deg HUD display cannot code the full range of possible pitch or yaw motion, whereas depiction of 360 degrees of roll motion in the frontal plane can occur without resorting to moving the background image.

Despite the confusions associated with the inside-out frame of reference, it may be contended that an "outside-in" display will prove even more perceptually disruptive because it is nonconformal to the retinal image of the outside visual world (i.e., the horizon, though perceptually stable, does in fact move during aircraft roll motion). If our perceptual system levels a tilted horizon to give us the perception of self-motion in a stable visual world, will it not also rotate a level HUD horizon by the same amount and thereby produce a perceived tilt in the attitude readout? Although this question requires further research, subjective reports from pilots suggest that AI motion may be perceptually decoupled from motion of the outside world during a roll. Hence, the AI's horizon may appear to tilt despite its conformance to the actual horizon, which appears stable. This rather paradoxical phenomenon may relate to an important principle derived from laboratory vection experiments: namely, our visual orientation system behaves differently for large background vs. small foreground visual stimuli (42,43). Indeed, it has been shown that an expansive, distant visual field exerts a strong influence over our orientation sense, whereas a small central field does not.

The reason for discounting motion in the proximal visual field is probably due to the nature of our perceptual experiences in that realm. For instance, movement of the limbs in near vision is often independent of our own bodily movements, while proximal images in moving vehicles are generally stabilized with respect to the body. In neither of these cases would visual motion (or its absence) be very useful in determining our orientation with respect to earth. Thus, cockpit display images, generally contained in the central 30 degrees of the visual field, are not perceptually stabilized in the same way that the ground and horizon are. Rather, such images are more likely to move in the same direction as the vestibular percept, as has been well-documented for the oculogyral and oculogravic illusions (10).

In summary, an analysis of the nature of visual-vestibular interactions in humans leads to the recommendation that a split frame of reference be used on the HUD attitude display, wherein aircraft roll is depicted using an outside-in perspective. Although optically nonconformal to the outside world, the outside-in perspective may ultimately prove much more consistent with the actual visual perceptual environment of flight.

CONCLUSIONS

Conceptual guidelines for a new HUD attitude symbology have been presented and discussed in the preceding sections, based on an understanding of the physiological and ecological basis of human visual perception. Several design recommendations are based on four fundamental aspects of visual perception:

- the 3-D structure of visual attention.
- global contour perception.
- preattentive cueing.
- visual-vestibular interactions in near vs. far visual space.

Although the proposed design features incorporate many recent perceptual discoveries and computer graphics capabilities, they may also be viewed as somewhat conservative in that they build upon previous concepts and displays. Indeed, the basic "T" arrangement, the round AI, the attempt to simulate the outside visual world, and the choice of a split frame of reference all represent traditional display concepts which are restored and expanded upon in the "physiological" HUD. A full HUD display incorporating the major design principles advocated in this paper would resemble the prototype shown in Figure 10.* In addition to its other features, this design limits the overall amount of digital and analog readouts and eliminates the moving-tape altimeter and airspeed scales. An expanded version of this display would be more important for landing (Figure 11), whereas a decluttered version would be more suitable in the weapon-delivery mode (Figure 12). Collectively, these and similar prototypes from other laboratories (15,23) offer the promise that a physiologically based HUD symbology--or at least major elements of it--may eventually be deployed on future USAF aircraft.

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* The USAF School of Aerospace Medicine has produced a videotape containing physiological HUD prototype displays with full motion. For information about the availability of this videotape, contact Dr. Previc.

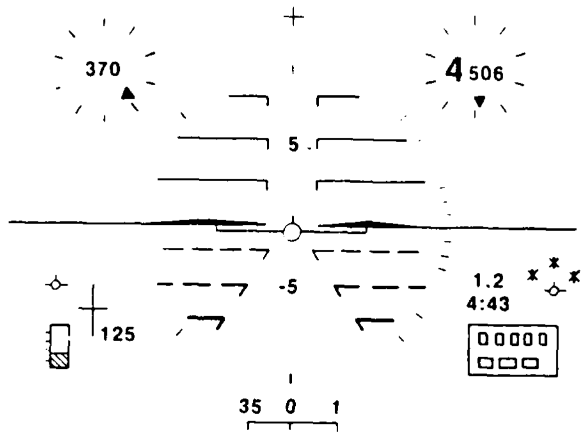

Figure 10. Full-format, prototype "physiological" HUD display.

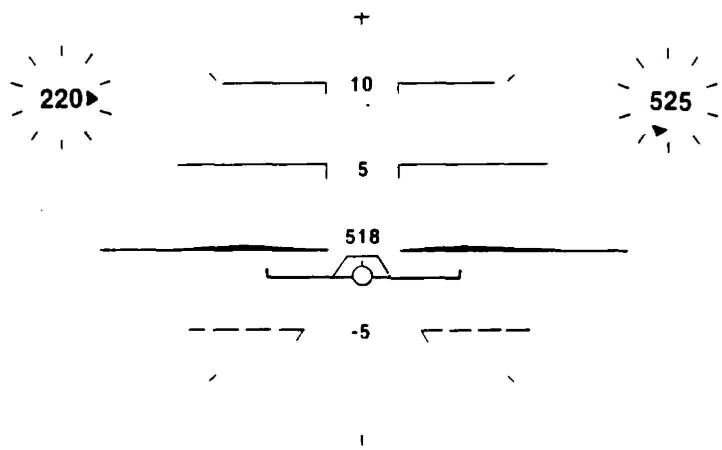

Figure 11. Prototype physiological HUD display designed for landing, which includes a simulated landing strip serving as a glideslope indicator.

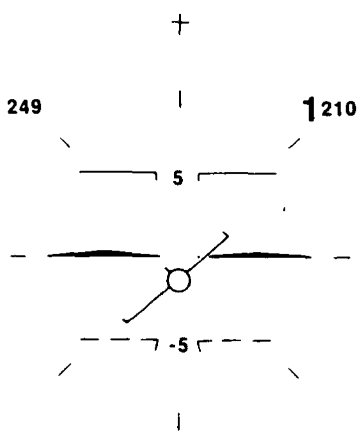

Figure 12. Prototype physiological HUD display in a decluttered weapons delivery mode.

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