N90-29828

Head-mounted spatial instruments II: [1] synthetic reality or impossible dream

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Abstract

A spatial instrument is defined as a spatial display which has been either geometrically or symbolically enhanced to enable a user to accomplish a particular task. Research we have conducted over the past several years on 3D spatial instruments has shown that perspective displays, even when viewed from the correct viewpoint, are subject to systematic viewer biases. These biases interfere with correct spatial judgements of the presented pictorial information. The design of spatial instruments may not only require the introduction of compensatory distortions to remove the naturally occurring biases but also may significantly benefit from the introduction of artificial distortions which enhance performance. These image manipulations, however, can cause a loss of visual-vestibular coordination and induce motion sickness. Consequently, the design of head-mounted spatial instruments will require an understanding of the tolerable limits of visual-vestibular discord.

Introduction

The introduction of relatively low cost, interactive, high performance 3D computer graphics work-stations such as the Personal IRIS or the Megatek 928, and the certain prospect for further miniaturization and cost reduction, has provided aerospace designers with powerful research tools for creating new media for interactive, information displays.

This flexibility raises many practical design challenges and interesting theoretical questions, but since many of these new information displays may be helmet or head mounted, particularly prominent questions concern guaranteeing the perceptual stability of the display's image. Indeed, it is argued in this paper that selecting a head-mounted format limits design freedom in the definition of the displays in ways that do not constrain conventional panel-mounted formats.

Analysis

An understanding of the relevant design questions is best provided by an analysis of the linear transformations that the spatial information must undergo before presentation to the user. In general, the information is first defined as sets of vectors, polygons, or polyhedra positioned in an inertial reference frame some times called the "real world" coordinate systems. (Foley and Van Dam, 1982).

Prior to presentation to the viewer, this information must be transformed by scaling, rotation, translation, and projection to position it in an "eye coordinate system" determined by the position and direction of a viewing vector. This transformation processes is commonly represented as a series of matrix operations and is referred to as the "viewing transformation", but as shown in Figure 1, it may be broken into several separable parts each of which allows a unique opportunities for the introduction of informative distortions.

Subsequent use of this spatial information by the viewer requires that he internally perform further coordinate transforms to bring it into a useful frame of reference. For example, if the subject is required to make an egocentric direction judgment based on information on a 3D map, he must further

[1]Earlier versions of this manuscript have been reported at the 1987 AGARD Meeting of the Aerospace Medicine Panel in Brussels, Belgium, September 28 - October 2, 1987 and at the 1988 California Mapping Conference, San Jose, California.

transform the information into a body or even a hand centered coordinate system by a process similar to the viewing transformation. These are the transformations typically required in telerobotics.

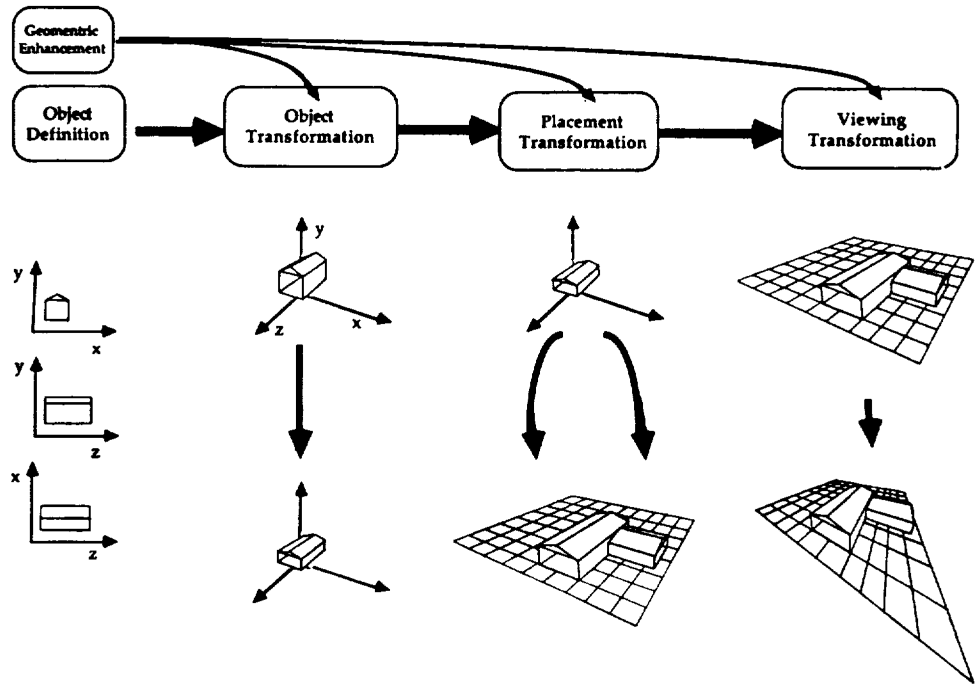


Figure 1. The process of representing a graphic object in the virtual space allows a number of different opportunities to introduce informative geometric distortions or enhancements. These may either be a modification of the transforming matrix during the process of image definition or they may be modifications of an element of a model. Often the matrix element or shape of the model part is controlled externally by a variable slewed to a mouse or other input device. These interventions may take place 1) in an object relative coordinate system used to define the object's shape or 2) in an affine or even curvilinear object transformation, or 3) during the placement transformation that positions the transformed object in world coordinates, or 4) in the viewing transformation. The perceptual consequences of informative distortions are different depending upon where they are introduced. For example, object transformations will not impair perceptual stability in a head-mounted display whereas manipulations of the viewing transformation will.

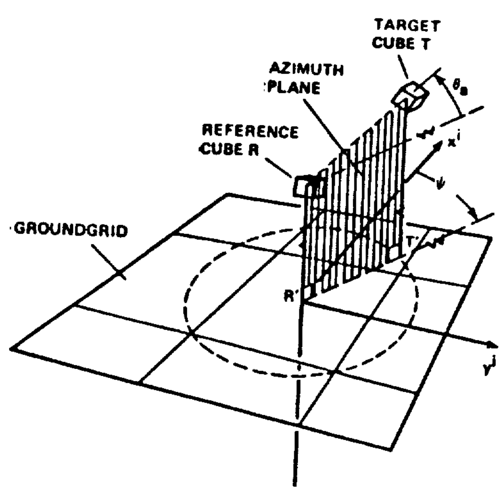


Figure 2. The relative direction of one cube with respect to another and a reference direction x is given by the difference in the judged egocentric azimuth rotation of two objects: the ground grid which provides the reference and the azimuth plane defined by perpendiculars dropped from the cubes to the grid. In order for a viewer to perceive the exocentric direction Ψ of the target cube he must recover the viewing parameters used to make the picture.

In order to understand how the spatial information presented in pictures may be used, it is helpful to distinguish between images which may be described as spatial displays and those that were designed to be spatial instruments. One may think of a spatial display as any systematic mapping of one space onto another. A picture or a photograph is a spatial display.

A spatial instrument, in contrast, is a spatial display that has been enhanced either by geometric or symbolic techniques to insure that the communicative intent of instrument is realized. A simple example of a spatial instrument is an analogue clock. In a clock the angular positions of the arms are made proportional to time, and the viewer's angle estimation task is assisted by radial tic marks designating the hours and minutes. A second aspect of the definition of a spatial instrument, which the clock example also illustrates, is that the communicated variable, time, is made proportional to a spatial property of the display, such as an angle, area, or length and is not simply encoded as a character string.

The spatial instruments that we wish to focus attention on are generally interactive. That is to say that the communicated information flows both to and fro between the viewer and the instrument. Some of this bidirectional flow exists for practically all spatial instruments since movement of the viewer's viewpoint can have a major impact on the appearance of the display. However, the displays we wish to consider are those incorporating at least one controlled element, such as a cursor, which is used to extract information from and input information to the instrument.

Maps also meet the definition of a spatial instrument. The map projection may be chosen depending upon the spatial property of importance. Choice of this projection illustrates objective geometric enhancement. Overlaying of a graticule of latitude and longitude lines indicating the map metric is an example of symbolic enhancement. When fitted with these enhancements, the map can become a nomographic calculating instrument for navigation or spatial orientation.

In selecting a map projection for a small scale map, such as a world map, a cartographer may select a projection from three families of perspective projections in which the solid angle formed at the point of contact between the globe and the projection surface varies 1) from 2π steradians, the zenithal case, 2) from 2π up to 0 steradians, the conical case, and 3) 0 steradians, the cylindrical case.

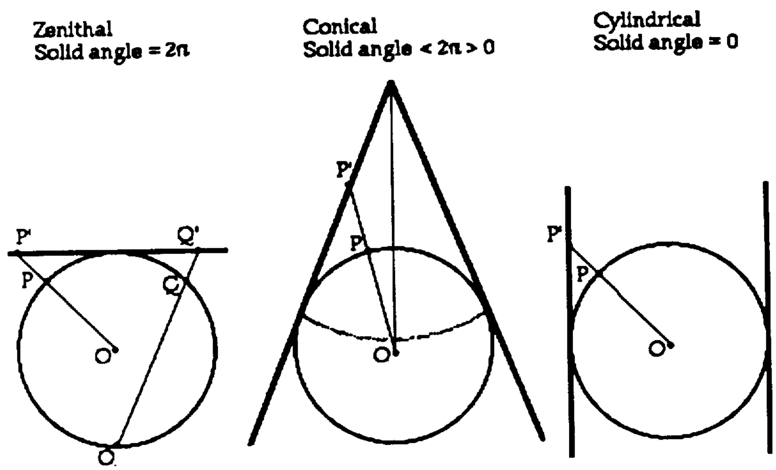


Figure 3. Geometric categories of map projections.

This selection can be guided by the ultimate use of the map. If, for example, a map is to be used to find minimum distance routes between distant points, a special case of the first type, the gnomonic projection can be used since it has the useful property of projecting all great circles as straight lines. (See Figure 4) One corresponding cost that must be incurred for this useful property is that the nonlinear scale distortion along meridians and parallels is unequal. Scale exaggeration for a piece of meridian in the vicinity of latitude θ is $cosec^2\theta$ and exaggeration of latitude scale is $cosec\theta$. The map is, thus, not orthomorphic, i.e. shape preserving (Cotter, 1966). Nonlinear scale distortions of this sort are, however, well understood and can be objectively controlled by selection of the point of contact of the projection and the extent of area represented on the map.

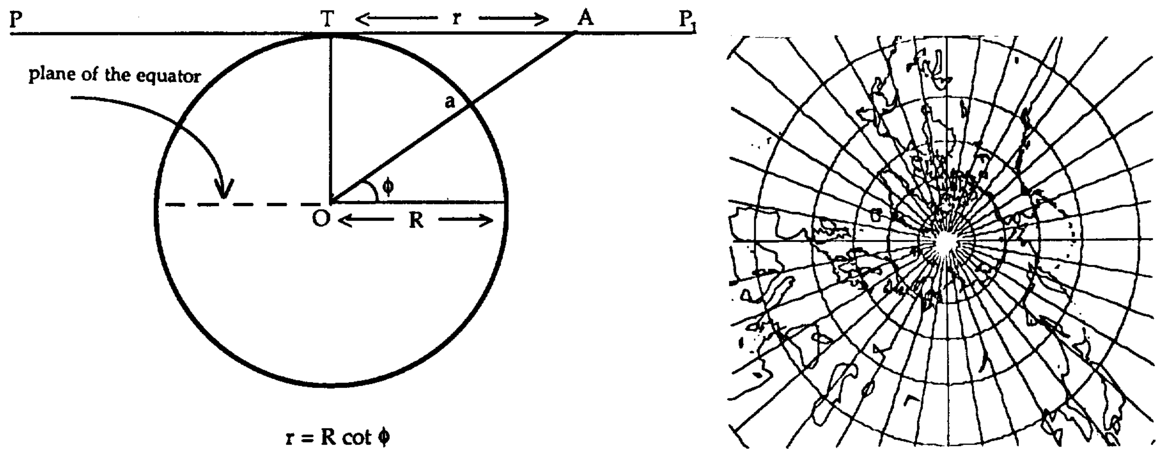


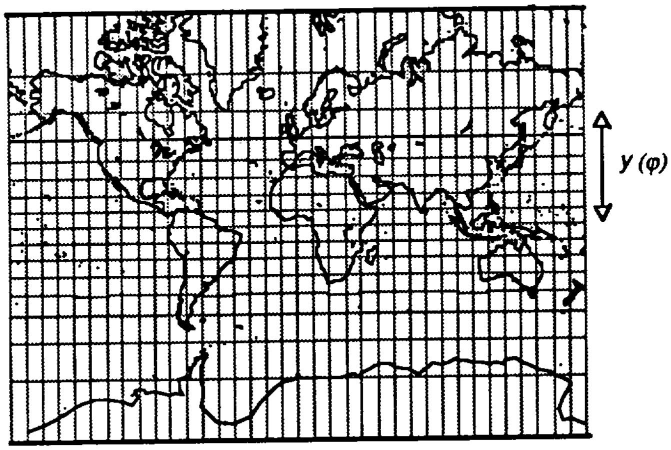
Figure 4. Geometry of radial scale exaggeration in a gnomonic projection with an example of a gnomonic projection centered on the north pole.

The distortions present on the gnomonic projection are a geometric consequence of the selected perspective parameters which describe the projection of the of the globe onto a tangent projection surface. They are not explicitly introduced but rather are a side-effect of the desired property that great circles map as straight lines. Distortion, however, can also be introduced directly into a projection to achieve a desired end as in popular conventional projections such as the mercator chart which is designed to map compass courses as straight lines. In this projection, a rectangular projection with the standard parallel set to the equator is intentionally distorted along the meridians to compensate for the fact that the scale along each parallel of the rectangular projection represents a smaller and smaller small circle as higher latitudes are mapped. Since the circumference, r, of a circle of latitude θ on a globe of radius R is: $r = R\cos(\theta)$. each small element of the meridian must be stretched by $1/\cos(\Theta)$ to compensate and straighten out the plots of oblique courses. The resulting scale exaggeration near the poles is so great to make the map unusable, but the technique works well for middle latitudes.

The geometry of gnomonic or mercator projections is well understood and adapted to provide geometric properties on the respective maps that are objectively useful. The straight line plotting of either great circles or rhumb lines facilitated use of the maps for navigation since desired courses could be found with a straight edge. Today in the time of computer-graphics based dynamic maps this advantage is not nearly as important. As is clearly evident from the software-based tools for interacting with spatial data bases as used for computer aided design, the old fashioned ruler and pencil have been generalized into multidimensional probes and almost magical cursors that can quickly extract highly dimensional spatial information from a data base which earlier generations of draftsman could barely imagine (Silicon Graphics, 1988; Dickinson, 1989ab). Consequently, the desired objective properties of images of spatial data are now not the same and in fact may be less important than the subjective appearance of the space depicted in the image. It is this subjective appearance that most directly influences the users interaction with the spatial data through his control of a cursor. Accordingly, the subjective appearance of the image now can become an important design feature.

Spatial Instruments

Contemporary spatial instruments are found throughout the modern aircraft cockpit, the most notable probably being the attitude direction indicator or ADI which displays a variety of signals related to the aircraft's attitude and orientation with respect to earth based navigation aids. More recent versions of these standard cockpit instruments have been realized with CRT, cathode ray tubes, based instruments which have generally been modeled after their electromechanical predecessors (Boeing, 1983).



$$y(\varphi) = \int_0^{\varphi} sec(\theta)\, d\theta$$

Figure 5. Compensatory distortion of a rectangular projection is illustrated by the change in scale along the meridians of the mercator projection.

The computer graphics and CRT display media, however, allow the conception of totally novel display formats for demanding new aerospace applications. Grunwald and Ellis (Grunwald and Ellis, 1988) have described, for instance, a more pictorial spatial instrument to assist informal, complex, orbital navigation, proximity operations, and rendezvous in the vicinity of the space station (see Figure 6). The definition of this instrument entailed a number of specific graphical enhancements which may be classified as either geometric, symbolic, or both. For example, a geometric enhancement was introduced by providing a display mode in which the axis along which spacecraft typically follow reentrant looped paths is transformed into a time axis which does not exhibit these loops. This transformation may assist obstacle avoidance and out of plane maneuvering during small orbital changes. The use of a time axis may also be a technique to avoid visual illusions associated with perspective projections of the trochoidal paths that describe the relative motion paths of one spacecraft with respect to each other.

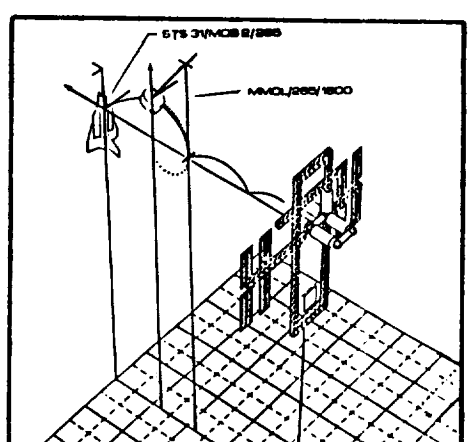


Figure 6. Sample proximity operations display. The solid curves lines show a planned orbital rendezvous between an orbital maneuvering vehicle (OMV) and the space station. The dotted line is a predicted flight path for the OMV. The projecting vectors show body axes of the craft.

Geometric Enhancement

In general, there are various kinds of geometric enhancements that may be introduced into spatial displays, but their common feature is a transformation of the metrics of either the displayed space or of the objects it contains. A more familiar example is found in relief topographic maps for which it is useful to exaggerate the vertical scale. This technique has also been used for experimental traffic displays for commercial aircraft. (Ellis, McGreevy, & Hitchcock, 1987)

Another type of geometric enhancement important for displays of objects in 3D space involves the choice of the position and orientation of the eye coordinate system used to calculate the projection. Azimuth, elevation and roll of the system may be selected to project objects of interest with a useful aspect. This selection is particularly important for displays without stereoscopic cues, but all types of displays can benefit from an appropriate selection of these parameters. (Ellis, Kim, Tyler, McGreevy and Stark, 1985; Kim, Ellis, Tyler, Hannaford, and Stark, 1987).

Because of its dramatic effect on the image, selection of the field of view angle is particularly interesting. Only changing the field of view angle simply magnifies the image producing image which corresponds to an optic array geometrically similar to that optic array that a viewer would experience from the modeled eye point. Selecting a very wide field of view angle results in a minimized image, but also can introduce marginal distortions if a planar projection surface is used to produce the image. An additional source of distortion can arise if the display is viewed from a point other than the modeled eye point in the eye coordinate system. The effects of these latter distortions may, however, be modulated by the viewer's awareness of the picture plane (Pirenne, 1970; Ellis, Smith, McGreevy, 1987).

Significant design features can be achieved by joint variation of the field of view angle as objects in the display (McGreevy and Ellis, 1986; Ellis, et al., 1987; Adams, 1975). Though this combined manipulation may introduce marginal distortions, it allows control over the projected sizes of objects in the image and, for example, allows definition of a projection that will always include a designated volume of the object space. This is a useful property of a situation awareness display which is not preserved in a display by changes in the field of view alone.

The introduction of deliberate spatial distortion into a spatial instrument can be a useful way to improve the communication of spatial information to a viewer since the distortion can be used to correct underlying natural biases in spatial judgements. For example, exocentric direction judgements (Howard, 1982) made of extended objects in perspective displays, can for some response measures exhibit a "telephoto bias". That is to say that the subjects behave as if they were looking at the display through a telephoto lens. This bias can be corrected by introduction of a compensating wide-angle distortion. (McGreevy and Ellis, 1986; Grunwald and Ellis, 1987)

Unnatural scaling by placement transformations can also be used to control an objects prominence, to insure, for example, that they never become vanishingly small. (see Figure 7). Scaling with an object transformation is also particularly effective at achieving nonlinear exaggerations but such unnatural object scaling can, however, increase display clutter: objects may interpenetrate. But independent scaling of the separate axes of the object generally provides the designer with techniques to reduce this interpenetration.

Symbolic Enhancement

Symbolic enhancements generally consist of objects, scales, or metrics that are introduced into a display to assist pick-up of the communicated information. The usefulness of such symbolic aids can be seen, for example, in displays to present air traffic situation information which focus attention on the relevant "variables" of a traffic encounter, such as relative altitude, as opposed to less useful "properties" of the aircraft state such as absolute altitude (Falzon, 1982).

One way to present an aircraft's altitude relative to a pilot's own ship on a perspective display is to draw a grid at a fixed altitude below the "ownship" symbol and drop reference lines from all aircraft symbols onto the grid. If the "ownship" altitude is marked on these reference lines, then the distance from the other aircraft symbol to the mark is proportional to the relative altitude. If the aircraft are given predictor vectors that show future position, similar reference lines can be dropped from the ends of the predictor lines.

The reference lines not only serve to clarify the target's ambiguous aspect but also can improve perception of the target's heading. This effect has been shown in a recent experiment examining the effects of reference lines on egocentric perception of azimuth of extended objects in perspective images created by a microcomputer graphics system. This experiment provides a specific example of how psychophysical evaluation of display formats can be used to assess their information display effectiveness.

In this experiment 10 subjects viewed static perspective projections of aircraft-like symbols elevated at three different levels above a ground reference grid: a low level below the view vector and almost on the grid, a middle level co-linear with the viewing vector, and a high level above the view vector by the same amount as the low level was below it (see Figure). The aircraft symbols have straight predictor vectors projecting forward showing future position above the reference grid. In one condition reference lines were dropped only from the current aircraft position. In the second condition reference lines were dropped also from the ends of lines projecting from each aircraft. These lines could represent predictors of future position.

The subjects viewed the entire configuration of aircraft symbol and grid from a fixed eye position 28 cm from the projection surface. This position was at the geometricaly correct center of projection for a viewing vector set to 0 degrees azimuth and -22.5 deg elevation. Nine different azimuth rotations of the image were presented: 0 to 180 in 22.5 degree increments. The subject's task was to adjust the egocentric direction of a horizontal dial to indicate the azimuth rotation of the aircraft. Azimuth rotation was crossed with number of reference lines in a factorial repeated measures experiment.

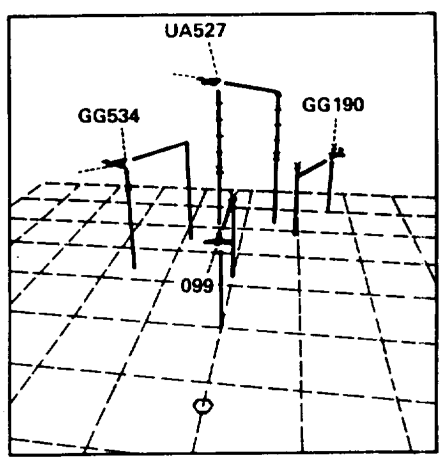


Figure 7. Sample cockpit display of air traffic. Own ship is at the center of the display. 1 minute predictors project out of all aircraft symbols. Reference line are dropped perpendicular to the reference grid.

The first result of the experiment was that subjects made a substantial errors in their estimation of the azimuth rotation of the aircraft; they generally saw it rotated more towards the picture plane than it in fact was.($F= 23.4$, $df = 8,72$; $p < .001$) This corresponded to clockwise errors for actual clockwise rotations up to 90 degrees. The errors reverse for rotations greater than 90 degrees.

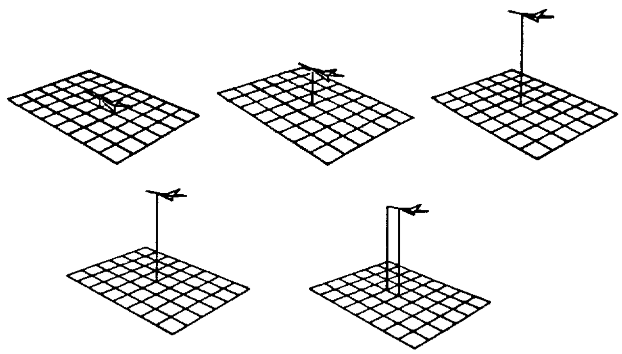


Figure 8. Five views of sample stimuli used which illustrate the three heights of the aircraft symbol above the grid and the two reference line conditions. Viewing elevation = -22.5 deg, azimuth = 45 degrees. As the aircraft rises away from the grid it develops an illusory yaw toward the picture plane.

The second result is that the the error towards the frontal plane for the symbols with one reference line increased as the height of the symbol increased above the grid ($F = 4.1$, $df = 2,18$, $p < .34$). Most significantly, however, as shown in Figure 9, introduction of the second reference line totally eliminated the effect of height, reducing the azimuth error in some cases about 50% ($F = 2.402$, $df = 16,144$, $p < .003$). A more detailed geometric and perceptual analysis of this result is beyond the scope of this paper; however, these experimental results show in a concrete way how appropriately chosen symbolic enhancements can provide not only qualitative but quantitative improvement in pictorial communication.

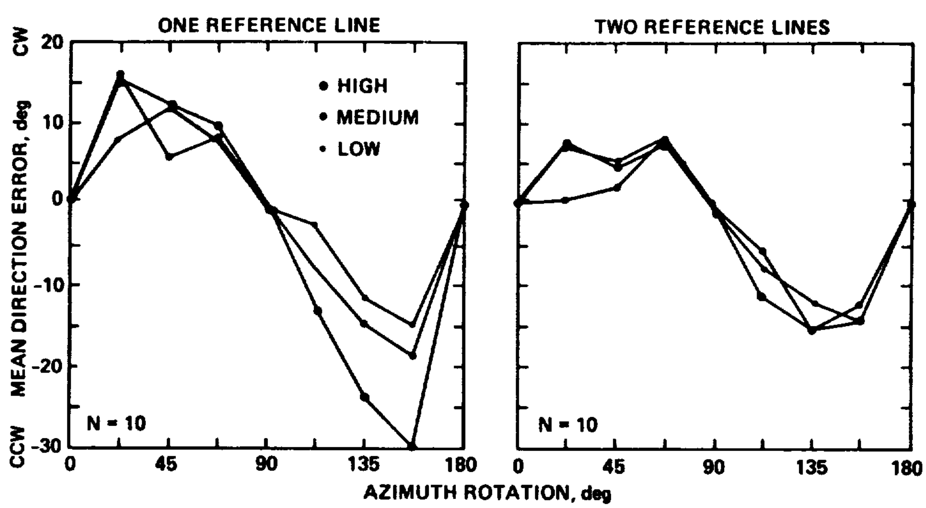


Figure 9. Mean clockwise and counterclockwise egocentric direction judgement for clockwise azimuth rotation.

Combined Geometric and Symbolic Enhancements

Some enhancements combine both symbolic and geometric elements. One good example is provided by techniques connecting the photometric properties of objects or regions in the display with other geometric properties of the objects or regions themselves. Russell and Miles (1987), for example, have associated the optical density of points in space with the norm of the gradient of the concentration of a dissolved component and produced striking visualization of three-dimensional distributions of the compound. Similar techniques have been applied to solid models derived from sequences of CAT scans and allowed a kind of "electronic dissection" of medical images by control of the transparency of the different tissue types contained in the X-ray images (Meagher, 1987). Though this technique can provide absolutely remarkable images; one could for example "see the wind" by making optical density proportional to velocity; one of the challenges of its use is the introduction of metrical aids to allow the viewer to pickup quantitative information from the photometric transformation.

Discussion

The different types of enhancement are important in particular for head-mounted displays because they interact differently with the image and viewer. The global geometric enhancements are particularly important for head-mounted displays since they interfere with visual-vestibular coordination and can result in motion sickness.

Computer generated, helmet-mounted images were probably first produced by Ivan Sutherland in 1970 (Sutherland, 1970) and have more recently been produced somewhat more elaborately at several other laboratories. (Furness, 1986; Fisher, McGreevy, Humphries, Robinett, 1986). When Sutherland developed his display, the required hardware and software investment was substantial and available only to well funded laboratories. In contrast today, the display technology has become so inexpensive that a system adequate for creditable research can be assembled within a budget of a few thousand dollars.

Presentation of the computer generated image display on a head mounted display strongly encourages the viewer to interpret the projection as a virtual space which is expected to interact with his movements as if it were a real space. This kind of interpretation also occurs, but to a lesser extent, with ordinary pictures presented in the normal panel mounted format. The interpretation of a virtual space can give rise to pictorial illusions of depicted orientation (Goldstein, 1987; Ellis, Smith, and McGreevy, 1987), but these effects are far weaker with panel mounted displays than with those that are helmet-mounted.

One reason for the difference is that the helmet displays often include collimating optics, (Weintraub et al., 1985) producing true virtual images and interfering with viewers ability to locate the surface of the picture (Nagata, 1986). Furthermore, the helmet displays generally present wider fields than the panel mounted displays. These viewing conditions, which trigger the normal binocular reflexes associated with vergence accommodation, coupled with the vestibular effects of head movement result in a viewing situation that requires careful calibration to insure perceptual stability. If stereoscopic presentation or head driven motion parallax are used, this requirement is assured.

The difficulty with this format is that the global geometric enhancements destroy the required calibration. This difficulty is true by definition for the enhancements, such as differential scaling of the display axes, that operate on the viewing transformation itself, but it is also true, though to a lesser extent, of enhancements such as differential object scaling because familiar size can be the overriding cue to apparent distance (Ittelson, 1951). This effect may have operational significance and explain errors pilots make when using virtual image displays (Roscoe, 1984; 1987).

The loss of visual stability due to improper correlation between visual and vestibular movement arises from both voluntary and involuntary head movement. Large voluntary head movements can produce the most obvious loss of stability if the gains and phase lags between the image movement and vestibular ocular reflex (VOR) do not match. Fortunately, the VOR is adaptable and can adjust its gain and phase response (Bertoz and Melville-Jones 1985), though time lags resembling transport delays may preclude this adaptation. Small involuntary head movements cause relative movement between the head and the viewing axis of the eye which is inertially stabilized by the VOR. In this situation the head-mounted display screen moves and blurs the image. Thus the normal operation of the VOR is actually counterproductive. Measurement of the actual head movement can provide a signal to allow compensatory, inertial stabilization of the display by displacement on the screen by adaptive filters which can model the VOR (Wells and Griffin, 1984; Velger *et al.*, 1988).

Besides loss of visual stability, geometric enhancements can interfere with visuo-motor coordination. This interference is particularly evident if the display includes a hand-controlled cursor. Under these circumstances an improperly calibrated or and intentionally distorted display resembles the view through a prism and lens system that introduces an optical distortion into the lines of sight. As known at least from the time of Helmholtz (1856), the visuo-motor system can completely adapt to the kind of conformal transformation such system can produce. Short time delays, on the order of 100 msec., can, however, substantially degrade or block this adaptation. (Held, Efstathiou, and Greene, 1966).

Allowable Enhancements for Helmet Mounted Instruments

In view of the many intrinsic problems with purely geometrical enhancement, the safest enhancements for helmet mounted instruments seem to be symbolic, the kind of added information overlays that have been used on aircraft head-up-displays for years.

These displays typically transpose much of the information already available in aircraft cockpits into a more integrated form and present it on a large combining plate, or beam splitter, so the information is available "head up" and can be seen when the pilot looks out the window (Weintaub, Haines and Randle, 1985). In addition to the usual moving tape, cursors, or numerical readouts, these displays often have a small graphics image projected to correspond in shape, size and position to an out-the-window object such as a runway. Maintaining good calibration for such an overlap between a display-generated graphics object and the projection of a real external object represents a significant challenge in a wearable helmet not using skull screws to maintain its position on the users head. Indeed, helmet mounted displays of this sort have been suggested as a useful nausea-inducing apparatus to attempt to habituate astronauts to the sensory discordance of weightlessness before they begin space travel. (Parker, Renschke, Arrott, Homick, and Lichtenberg, 1986).

Never the less, symbolic use of three-dimensions also seems to be an allowable enhancement. For example, one can imagine three-dimensional icons representing records in a hierarchical data base for which the third dimension could represent depth of nesting. Another interesting possibility for symbolic aid could be transient 3D "yardsticks" used in combination with a 3D cursor to designate pairs of objects to be compared. Once two objects are selected, a line symbolically designating their separation could be temporarily generated to display a binary relation between them.

Among the geometric enhancement, those least likely to cause visual stability problems are those that act on the real world coordinates of the displayed objects themselves: the object scaling transformations. Provided that the transformed objects do not markedly violate the viewers implicit assumptions about size and shape, these transformations act early enough so that their effect may interpreted simply as changing the shape and size of the objects. They would unfortunately interfere with manual manipulation of the objects, but as long as this is carried out symbolically with a cursor and not with a simulated "hand" with many degrees of control which must be adapted to the conditions of the display space, these size and shape transformation should not be too aversive.

Finally, the photometric transformation illustrated by Russell and Miles (1987) is unlikely to have untoward consequences for head mounted instruments and may prove useful if combined with metrical aids allowing them to present more quantitative information.

In the final analysis the basic limits in the definition of helmet mounted instruments may not be classically technological, but intellectual. The technological limits faced in the design of these tools will be foreseeably over come by time and effort of others involved with the seemingly inevitable progress of optical and electronic fabrication. The intellectual limits will be overcome only by designers imagination and understanding of human spatial perception.

References

Adams, Ansel. (1975) *Camera and lens.* Morgan and Morgan, New York

Bertoz, A. and Melville-Jones, G. (1985) *Adaptive mechanisms in gaze control: facts and theories.* Elsevier, New York.

Boeing (March, 1983) 757/757 Flight deck design development and philosophy, D6T11260-358. Seattle.

Cotter, Charles H. (1966) *The astronomical and mathematical foundations of geography* . New York, Elsevier

Dickinson, Robert (1989a) A unified approach to the design of visualization software for the analysis of field problems. *SPIE/SPSE Symposium on Electronic Imagining,* Conference 1083 vol 1083.

Dickinson, Robert (1989b) Interactive 4D visualization of fields with applications including meteorology, FEM, CFD, analyses and molecular fields. (Submitted for publication SIGGRAPH89.)

Ellis, S.R., Kim, Won Soo, Tyler, Mitchell, McGreevy, M. W. , Stark, L. (Nov., 1985). Visual enhancements for perspective displays: perspective parameters. *Proceedings of the 1985 International Conference on Systems Man and Cybernetics.* IEEE Catalog # 85CH2253-3, 815-818.

Ellis, Stephen R., Kin, Won-Soo, Tyler, Mitchell, Stark, Lawrence. (1985). *Proceedings of the 1985 International Conference on Systems, Man, and Cybernetics* (pp.815-818). New York: IEEE.

Ellis, Stephen R., Smith, Stephen, McGreevy, Michael W. (1987) Distortions of perceived visual directions out of pictures. *Perception and Psychophysics, 42,* 535-544.

Ellis, Stephen R., Grunwald, Arthur. (1987) A new visual illusion of projected three-dimensional space. *NASA TM 100006,* NASA Ames Research Center., Moffett Field, CA,

Falzon, P. (1982, June). Display structures: compatibility with the operators mental representations an reasoning processes. *Proceedings of the 2nd European Annual Conference on Human Decision Making and Manual Control.,* 297-305). Wachtberg-Werthoven, Federal Republic of Germany: Forschungsinstitut fuer Anthropotechnik.

Fisher, S.S., McGreevy, M.W., Humphries, J., Robinett, W. (1986) Virtual environment display system. ACM 1986 Workshop on 3D Interactive Graphics, Chapel Hill, North Carolina. October 23-24, 1986

Foley, J.D. and Van Dam (1982) *Fundmentals of interactive computer graphics.* Addision-Wesley, Reading, Mass.

Furness, Thomas F. (1986) The super cockpit and its human factors challenges. *Proceeding of the Human Factors Society, 30th Annual Meeting,* 48-52.

Held, Richard, Efstathiou, Aglaia, and Greene, Martha. (1966) Adaptation to displaced and delayed visual feedback from the hand. *Journal of Experimental Psychology, 72,* 887-891.

Ittelson, W. H. (1951) Size as a cue to distance: static localization. *American Journal of Psychology, 64,* 54-67.

Glickstein, Mitchel (September, 1988) The discovery of the visual cortex. *Scientific American.*

Goldstein, E. Bruce (1987) Spatial layout, orientation relative to the observer, and perceived projection in pictures viewed at an angle. *Journal of Experimental Psychology, 13,* 256-266.

Grunwald, Arthur, & Ellis, Stephen R. (1986) Spatial orientation by familiarity cues. *Proceedings of the 6th European Annual Conference on Manual Control,* June, 1986, University of Keele, Great Britain.

Grunwald, Arthur, & Ellis, Stephen R. (1988) Interactive orbital proximity operations planning system. *NASA TP 2839* , November, 1988.

Helmholtz, H. *Handbook of physiological optics* (1856-1866) Southall trans. Optical Society of America (1924), Rochester, N.Y..

Herbst, P.J., Wolff, D.E., Ewing, D. and Jones, L.R. (1946, February). The TELERAN proposal. *Electronics, 19,* 125-127.

Howard, Ian. (1982) *Human visual orientation.* Wiley, New York.

Jenks, George F. and Brown, D. A. (1966). Three dimensional map construction. *Science,* 154, 857-846.

Kim, W. S., Ellis,S.R., Tyler, M., Hannaford,B., & Stark, L. (1987) A quantitative evaluation of perspective and stereoscopic displays in three-axis manual tracking tasks, *IEEE Trans. on Systems Man and Cybernetics, SMC- 17,*61-71.8

McGreevy, Michael W., Ellis, Stephen R. (1986) The effects of perspective geometry on judged direction in spatial information instruments. *Human Factors, 28,* pp. 421-438.

Meagher, Donald J. (1987) The manipulation, analysis and display of 3D medical objects using octree encoding techniques. *Innovation et Technology en Biologie et Medecine,* 8, Special 1, 21-36.

Muybridge, Eduward. (1975) *Animals in Motion,* Lewis S Brown, ed., Dover, New York.

Nagata, S. (1986) How to reinforce perception of depth in single two-dimensional pictures. Selected papers in basic researches, No 44-51, *Proceedings of the 1984 SID*, 25, No. 3, 239-246.

Parker, D.E., Renschke, M.F., Arrott, A.P., Homick, J., Lichtenberg, B. (1986) Otolyth tilt-translation reinterpretation following prolonger weightlessness: implications for preflight training. *Aviation, Space, and Environmental Medicine, 56*, 601-606.

Piaget, J, and Inhelder, B (1956) *The childs conception of space.* Routledge and Kegan Paul, London.

Roscoe, S.N. (1984) Judgements of size and distance with imaging displays. *Human Factors, 26*, 617-629..

Roscoe, S.N. (1987) The trouble with HUDs and HMDs. *Human Factors Society Bulletin, 30*, 7, 1-3.

Russell, Gregory, Miles, Richard B. (1987) Display and perception of 3-D space-filling data. *Applied Optics*, 26, 973-982.

Sutherland, Ivan E. (1970) Computer displays. *Scientific American, 222*, 57-81.

Velger, Mordekai. (1988) Adaptive filtering of biodynamic stick feed-through in manipulation tasks on board moving platforms. *Journal of Guidance and Control Dynamics, 11*, 153-158

Weintraub, D.J., Haines, R.F., Randle, R.J. (1985) Head up display: HUD utility II: runway to HUD. *Proceedings of the 29th Meeting of the Human Factors Society.* University of Michigan, Ann Arbor.

Wells, Maxwell, Griffin, Michael J. (January, 1984) Benefits of helmet-mounted display image stabilisation under whole body vibration. *Aviation, Space and Environmental Medicine*, 13-18