Effect of Geometric Field of View on Stereoscopic Spatial Judgments

Peter Banton, Peter Thompson, and **Philip T. Quinlan,** University of York, England

Within a stereoscopic display the field of view (FOV) was held constant at 13.86° while the geometric field of view (GFOV) was varied across four levels: 0° (parallel), 13.86° (veridical), 50° and 100°. Participants performed a distance-matching task where they adjusted the distance of a *standard* track from the centre of the display to match the distance of a *target* track from the same point. The results indicated that while the least error occurred in the veridical GFOV condition, small variations of GFOV away from the veridical have little effect. Large differences between FOV and GFOV (36° and 86°) increased errors markedly. A trend toward better performance in the veridical GFOV condition relative to the parallel GFOV condition suggests that the use of linear perspective information in a stereoscopic display may facilitate more accurate spatial perception.

Actual or potential applications of this work include stereoscopic display design in aviation and non-aviation settings.

INTRODUCTION

Traditionally, pilots have used a two-dimensional (2D) plan-position display to gain position information about other aircraft in the vicinity. A plan-position display is viewed from a viewpoint elevation of 90° – that is, directly above the pilot's own position (Figure 1a). This affords accurate depiction of the relative azimuthal position of other aircraft but no pictorial information about their relative altitude. The complete three-dimensional (3D) picture must be synthesized from the plan-position display and a numerical altitude readout (or possibly an additional 2D side-elevation display).

By lowering the viewpoint elevation of the display from 90° to around 45° and relying on linear perspective to convey the impression of depth, a pseudo-3D display can be created (Figure 1b). The limitations of current 2D plan-position displays have been illustrated by many studies that demonstrate performance gains when additional, pseudo-3D, spatial information is displayed. For example, operators using 2D plan-view displays perform less well than operators using pseudo-3D displays on measures such as threat detection accuracy, response time, and number of vertical versus horizontal avoidance maneuvers (Bemis, Leeds, & Winer, 1988; Ellis, McGreevy, & Hitchcock, 1987).

However, perspective displays have the inherent disadvantage of incorporating geometric distortions that affect the accuracy of spatial judgments. The technique of constructing a perspective depiction of a 3D volume on a 2D surface involves choosing a center of projection (COP) and projecting the 3D object from the COP onto the display surface (Figure 2a). The depth dimension is collapsed onto the two dimensions of the display surface (see Foley, van Dam, Feiner, & Hughes, 1990, for a comprehensive treatment of this subject). Linear perspective conveys the missing depth information but at the cost of compressing the image proportionally to the depth represented. In a 90° viewpoint-elevation display format, the altitude dimension is maximally compressed

Address correspondence to Peter Banton, Department of Psychology, University of York, York, YO10 5DD, UK; p.banton@psych.york.ac.uk. **HUMAN FACTORS,** Vol. 43, No. 3, Fall 2001, pp. 405–414.

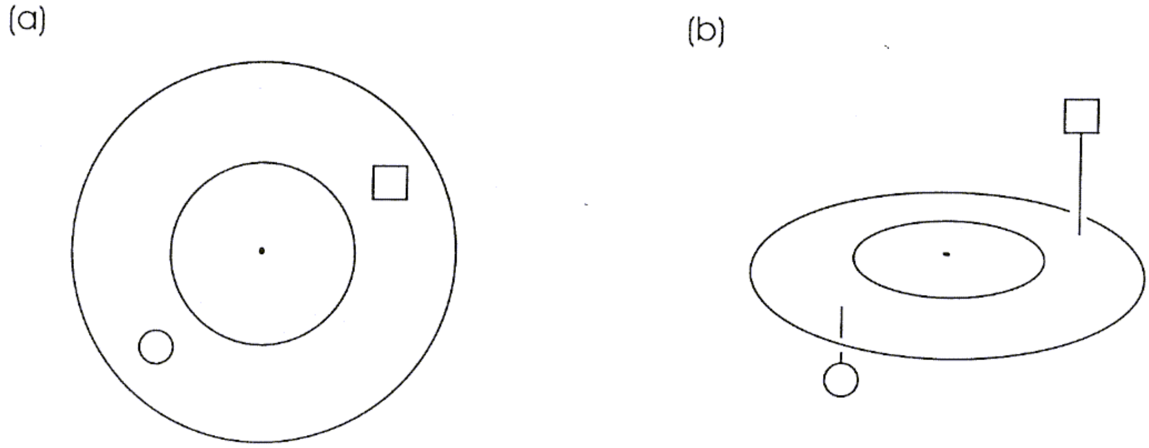

Figure 1. (a) 2D, 90° viewpoint-elevation display. (b) Pseudo-3D, 45° viewpoint-elevation display with drop lines from symbols to range rings.

whereas the azimuth dimension is unaffected. In a 45° viewpoint-elevation display format, the compression of information is shared between two spatial dimensions, and hence the compressive effect is reduced along each dimension (Hendrix & Barfield, 1997).

Previous research has largely concentrated on optimizing displays of a pseudo-3D perspective format. Designers of perspective displays have developed geometric enhancements such as reference grids and drop lines from symbols to the reference grid (e.g., Bemis et al., 1988; Ellis & Hacisalihzade, 1990; Kim, Ellis, Tyler, Hannaford, & Stark, 1987) to address the problem of ambiguous or degraded spatial information within these displays. These additions, although adding to the general "clutter" of the display, have met with some success. For example, when both reference grid and drop lines were employed in a pseudo-3D perspective display, normalized root mean square errors in a manual object-tracking task dropped from approximately .75 to approximately .40 (Kim et al., 1987).

Another parameter of perspective projection to receive attention from investigators is the display geometric field of view (GFOV) and its relation to field of view (FOV). The display FOV is defined as the angle subtended from the viewer's position (VP) to the edges of the "view window" (the display screen, in this case). The display GFOV is defined as the angle subtended from the COP to the edges of the view window (Figure 2b). When the FOV and the GFOV are the same (i.e., the VP and COP coincide), a veridical projection is obtained: a geometrically exact reproduction of the object being projected. Any difference between the display FOV and the GFOV results in a perceived distortion of the projected image (cf. McGreevy & Ellis, 1986). GFOVs greater than the FOV result in a fish-eye lens effect: large perspective distortions and a minification of the image. GFOVs smaller than the FOV produce a telephoto lens effect: smaller perspective distortions and a magnification of the image.

An early attempt by Kim, Tendick, and Stark (1993) to manipulate the difference between FOV and GFOV in a perspective display was confounded by the magnification/minification effect of the manipulation. In their study, either increasing the difference between the display FOV and GFOV or reducing the size of the display resulted in exactly the same reduction in performance. Thus this effect cannot be attributed to the FOV-GFOV difference.

McGreevy and Ellis (1986) separated the effects of perspective distortion and image scaling attributable to FOV-GFOV differences by locally scaling their displays to permit perspective distortion effects while eliminating the effects of magnification and minification of their target and reference cubes. Thus, in their display, the target and reference cubes were scaled to maintain the image size of the reference cube across GFOV conditions. The perspective distortion attributable to FOV-GFOV

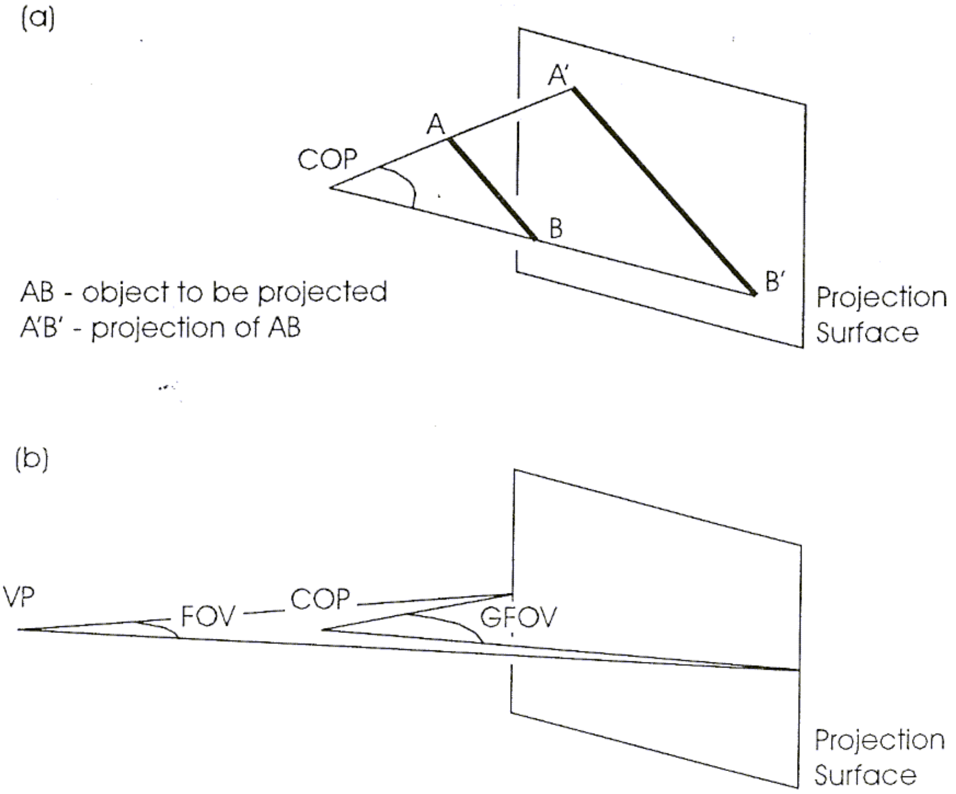

Figure 2. (a) Perspective projection geometry. (b) Relationship of FOV and GFOV for noncoincident VP and COP.

differences was evidenced mainly by distortions of the target cube and reference grid.

Although participants' estimates of target elevation and azimuth varied with other parameters, McGreevy and Ellis (1986) found that when their display GFOV was varied between 30° and 120°, the minimum overall error was in the 60° GFOV condition. As far as it is possible to ascertain from the viewing parameters stated in their paper, the 60° GFOV was the closest of their GFOV conditions to a veridical perspective projection of the scene.

Rosenberg and Barfield (1995) investigated a much smaller range of FOV-GFOV differences. They compared errors in participants' estimates of the "skewedness" of the projections of two parallel vertical lines in a display similar to that used by McGreevy and Ellis (1986). The display GFOV was varied between 50° and 70° and the FOV remained at 43°, but no effect of FOV-GFOV difference was found on their dependent variable. This suggests that relatively large differences (in excess of 30°) between FOV and GFOV are required to affect performance.

A different approach to the problem of degraded spatial information is to add stereoscopic depth information to a pseudo-3D perspective display, thus creating a truly 3D display format. Several studies have shown that stereoscopic information enhances performance relative to that of monoscopic pseudo-3D displays. This is especially true when monocular depth cues are few or ambiguous (Barfield & Rosenberg, 1995; Kim et al., 1987, 1993; Yeh & Silverstein, 1992). These results suggest that it may not be necessary to use reference grids and drop lines within a perspective stereoscopic display, eliminating a potential source of display clutter.

It is important to note at this point that the discussion so far has proceeded along a traditional route. The limitations of 2D displays have been addressed by the addition of depth information in the form of perspective. The addition of geometric enhancements and stereoscopic depth cues has been used to counter the problems of depth ambiguity caused by line-of-sight compression inherent in perspective displays. However, the addition of stereoscopic depth cues to an existing perspective display begs the question as to whether or not the use of linear perspective information is worthwhile in a stereoscopic display.

The present experiment was inspired by McGreevy and Ellis's (1986) investigation of a pseudo-3D perspective display. We manipulated the GFOV of a stereoscopic display between the nonperspective case (parallel projection: 0° GFOV) and a GFOV of 100° while maintaining a constant FOV. In order to investigate the effects of GFOV manipulations per se on performance within a stereoscopic display, an experiment was performed in which perspective distortions attributable to GFOV manipulations were separated from the consequent image-size changes in a manner similar to that adopted by McGreevy and Ellis (1986). By employing scaling to control for image-size effects, we aimed to establish whether perspective representations confer performance advantages over parallel representations and what effect the manipulation of FOV-GFOV differences within a stereoscopic display has on performance.

The display used in the present experiment was a stereoscopic 90° viewpoint-elevation, radar-like display comprising three concentric range rings within a wire-frame box that delimited the display volume (Figure 3). Across GFOV levels the range-ring plane of the display was scaled to maintain a constant image size, thus avoiding the confound of image-size changes with differing GFOVs.

A weakness of previous research on pseudo-3D displays has been that although different GFOVs were investigated, no explicit reference has been made to the veridical GFOV. Given that the perspective distortions involved depend on the difference between FOV and GFOV angles, this makes comparisons difficult.

In the present experiment, three alternative GFOVs were compared with the veridical GFOV.

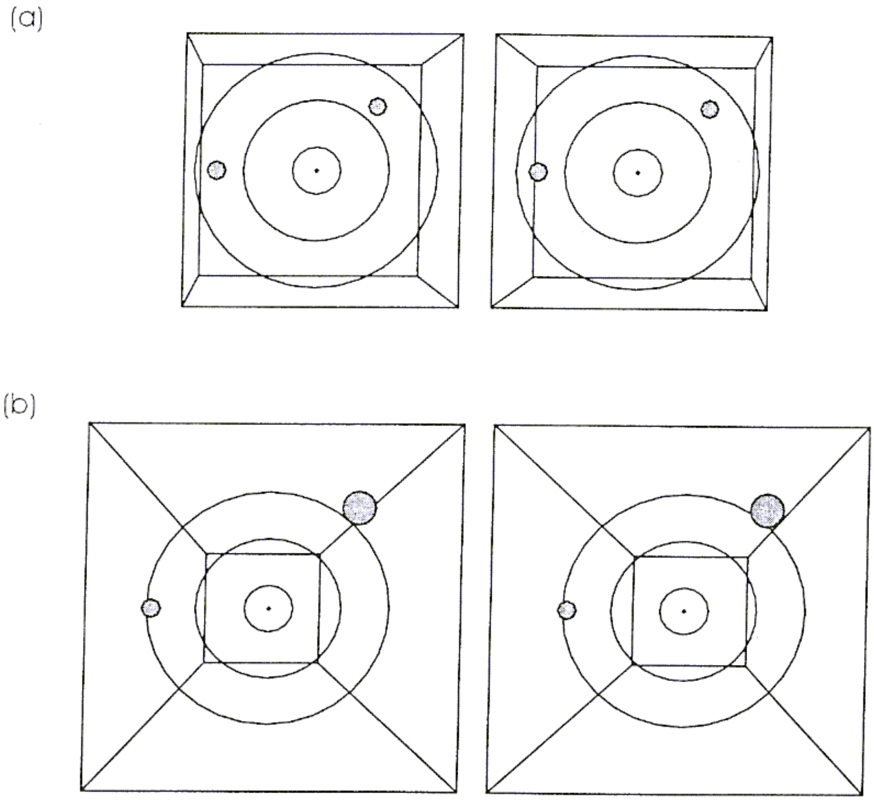

Figure 3. (a) Stereo pair showing veridical display with standard symbol and target symbol at azimuth/elevation 270°/0° and 45°/–45°, respectively. (b) Stereo pair showing 100° GFOV with standard symbol and target symbol at azimuth/elevation 270°/0° and 45°/45°, respectively. The stereo effect can be obtained either by free fusion or by use of a stereo viewer.

The display GFOV was manipulated over four levels: 0° (parallel projection), 13.86° (veridical projection), 50°, and 100°.

In most previous studies, the task has been one of position estimation by azimuth and elevation angle judgment (e.g., Ellis, Smith, Grünwald, & McGreevy, 1993; McGreevy & Ellis, 1986), categorization (e.g., Bemis et al., 1988), or target tracking (e.g., Kim et al., 1987, 1993; Way, Hobbs, Qualy-White, & Gilmour, 1990). Because both position and distance information are crucial to an accurate 3D impression, the dependent measure in the present experiment was chosen to examine the ability of participants to judge the distance from their indicated position to that of displayed objects.

METHOD

Participants

Five male and three female psychology undergraduates, age 19 to 28 years, participated in the experiment. All participants had normal or corrected-to-normal visual acuity (6:6 Snellen chart), stereoscopic acuity of at least 40 arcmin (Titmus test) and normal color vision (Ishihara, 1966).

Design

A 4 (GFOV) × 3 (azimuth) × 3 (elevation) within-subjects factorial design was used. The four levels of GFOV were 0° (parallel projection), 13.86° (veridical projection), 50°, and 100°. Symbol azimuth was varied over three levels: 0°, 45°, and 90°. Symbol elevation was varied over five levels: –90°, –45°, 0°, 45°, and 90° relative to the range-ring plane, where the 45° and 90° symbol elevations were nearer to the viewer than the range-ring plane. The ±90° symbol elevations were not crossed with the three symbol azimuths and were analyzed separately.

The experimental trials were blocked over GFOV conditions; participants performed each GFOV block on separate days. GFOV block order was randomized across participants, and within each GFOV block 18 repetitions of each symbol elevation and symbol azimuth combination were randomly ordered. Thus participants performed 162 trials in each GFOV block, making 648 trials in total.

Apparatus and Stimuli

The stimuli were presented on an Eizo Flexiscan T560 color monitor (Elizo Nanao; Ishikawa, Japan) driven by a Cambridge Research Systems (CRS; Rochester, England) VSG 2.2 graphics card housed in a 133 MHz PC. The stereoscopic images were created by sequentially interleaving left- and right-eye views on the monitor screen at the rate of 120 Hz, thus refreshing the stereoscopic image at the rate of 60 Hz. A pair of CRS FE1 ferroelectric shuttering goggles fed the alternating left- and right-eye images to their respective eyes. Participants sat at a constant viewing distance of 740 mm from the display (giving an invariant display FOV of 13.86°). A chin rest was used to minimize head movements.

The general design of the stimuli was that of a radar-like display similar to that used by Bemis et al. (1988). Figure 3 shows two stereo pairs of the display (veridical and 100° GFOVs), which comprised a blue range-ring plane, diameter 72 mm (of invariant size across GFOV conditions), centered within a blue wire-frame box that delimited the 3D volume of the display. The wire-frame box was the projection of a cube with a side length of 72 mm. The range-ring plane was fixed in the plane of the monitor screen (the plane of zero binocular parallax) midway between the near and far faces of the surrounding wire-frame box.

Within the display were placed two symbols. The *standard* symbol always appeared in the range-ring plane (i.e., elevation = 0°) at the 270° azimuth; its radial distance from the center of the display was adjustable by the participant. The *target* symbol was placed at one of three different azimuths and five different elevations (spherical coordinates) relative to the center of the display (see Design section).

The target and standard symbols were red circles with a 1-pixel-wide white border 0.26° in diameter at the range-ring plane. The diameter of the target symbol varied across GFOV conditions and symbol elevation, with the greatest range of diameters in the 100° GFOV condition. In this condition, the target symbol diameter varied from a minimum of 0.19° to a maximum of 0.46° for the –45° elevation and the 45° elevation, respectively.

In addition to the stereoscopic information, linear perspective and occlusion depth cues were available to participants. The retinal size of the target symbols changed with depth, and for all objects in the display (symbols, range rings, wire-frame box) objects farther from the observer were occluded by nearer objects. In the special case where symbols and range rings/wire-frame box were at the same distance from the observer, the symbols occluded all other objects. Target and standard symbols were never in a position to occlude each other.

With the exception of those symbol positions within the range-ring plane and those on the centerline of the display (the line from the COP passing through the centers of the front and rear faces of the wire-frame box and that of the range-ring plane), there was an effect on the relative positions of symbol, range rings, and wire-frame box attributable to GFOV condition. Because the standard symbol was within the range-ring plane, it was not affected; the effect on the target symbol was dependent on its elevation.

In general, GFOV angles larger than veridical compress points in the display volume toward the centerline of the display for elevations below the range-ring plane. For elevations above the range-ring plane, GFOV angles larger than veridical expand points away from the display centerline (see Figures 3a and 3b). These displacements increase with increasing elevation angle; thus the largest displacements occurred at the front and rear faces of the wire-frame box.

The perspective projections for each GFOV were produced by placing the COP at varying distances from the display screen. These distances were 75.5 mm, 193 mm, 740 mm, and infinity for the 100°, 50°, veridical, and parallel GFOVs, respectively.

The maximum binocular disparities in the display occurred at the front (–15.86 arcmin) and rear (15.86 arcmin) faces of the wire-frame box and were constant over GFOV conditions. The visual angles subtended by the front and rear faces of the wire-frame box varied with GFOV condition. The front face varied between 5.85° and 10.62° and the rear face varied between 5.31° and 3.78°, for the veridical and 100° GFOV conditions, respectively. The geometrical radial displacement of the target from the center of the real-world volume varied between a minimum of 33 mm and a maximum of 47 mm.

Procedure

The participants' task was to adjust the distance of the standard symbol from the center of the display to match that of the target symbol from the center of the display. Participants were given 20 practice trials, 10 on each of two randomly chosen GFOV angles. During the practice trials, any questions were answered but no feedback on accuracy was given. After completion of the practice trials, the experimental trials commenced. On each trial the target symbol appeared at a randomly chosen azimuth/elevation position and the standard symbol appeared at a randomly chosen position along the 270° azimuth radial within the range-ring plane (0° elevation).

Participants used two buttons to move the standard symbol nearer to, or farther from, the center of the display along the 270° azimuth. They pressed a third button to record their response and to commence a new trial. Participants were instructed to respond as accurately as possible; no emphasis was placed on speed of response.

RESULTS

Each radial displacement of the target from the center of the real-world volume was normalized to 1, and participants' distance-matching errors were calculated as a proportion of this value. As the azimuthal value of the ±90° target elevations was constant at 0°, these data were analyzed separately from the –45°, 0°, and +45° elevation data.

0° Elevation

From Figure 4 it is clear that participants responded quite differently in the 0° elevation condition relative to the ±45° elevation conditions. The 0° elevation data were entered into a two-way, repeated-measures analysis of variance (ANOVA). None of the effects reached statistical significance.

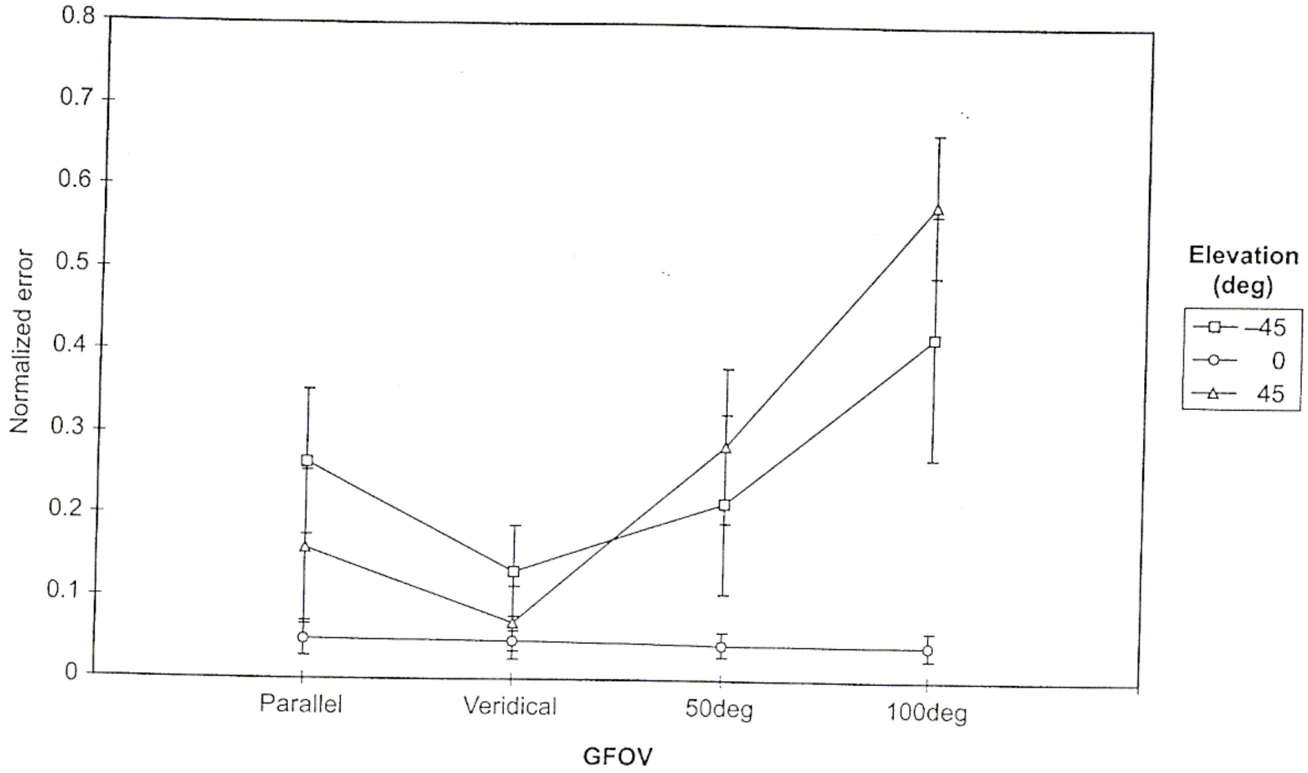

Figure 4. Effect of GFOV on radial distance matching error for 0° and ±45° elevations.

±45° Elevations

The ±45° elevation data were entered into a three-way, repeated-measures ANOVA. The ANOVA indicated significant effects of GFOV, $F(3, 21) = 12.74$, $p < .01$, GFOV by target-elevation interaction, $F(3, 21) = 9.61$, $p < .01$, and target-azimuth by target-elevation interaction $F(2, 14) = 5.45$, $p < .05$.

Interactions

As there was no target-azimuth by GFOV interaction, we collapsed the data across GFOV to investigate the target azimuth by target elevation interaction. A simple main effects analysis indicated this effect was attributable to a decrease of approximately 20% in distance-matching error between the 0° and 90° target azimuths for the –45° target elevation ($p < .05$). The distance-matching error remained constant across target azimuths in the 45° target elevation.

To explore the GFOV by target elevation interaction, we collapsed the data across target azimuth. A simple main effects analysis indicated a marginally significant difference ($p = .053$) between the 45° and the –45° target elevations at the parallel GFOV and differences approaching significance at the 50° ($p = .076$) and 100° ($p = .07$) GFOVs. No significant difference was found at the veridical GFOV.

Main Effect

Contrast analysis showed significant differences between the veridical and 50° GFOVs ($p < .05$) and between the 100° GFOV and the parallel, veridical, and 50° GFOVs ($p < .01$).

±90° Elevations

The ±90° elevation data (Figure 5) were entered into a two-way, repeated-measures ANOVA. A significant effect of GFOV was found, $F(3, 21) = 3.232$, $p < .05$. No other effects reached significance. A contrast analysis showed a significant difference between the veridical and 100° GFOVs ($p < .05$) and a difference approaching significance between the veridical and 50° GFOVs.

DISCUSSION

The data show that participants consistently overestimated distances between the target and the center of the display in all target-elevation and target-azimuth conditions. The magnitude of these overestimations varied as a function of GFOV and target elevation.

The minimum overestimation occurred for all GFOVs in the 0° target-elevation condition and shows a constant error. Because there is no geometrical effect of GFOV manipulations for symbols in the plane of the range rings, we expected the effect of GFOV manipulation to be least in this condition.

The magnitude of the overestimations found in the 0° target-elevation condition of the present study are comparable to those found by Norman, Todd, Perotti, and Tittle (1996) and McKee, Levi, and Bowne (1990). Norman et al. investigated line-length discrimination for lines oriented in both the frontoparallel plane and in stereoscopic depth. They found that participants' errors were around 5% for lines oriented in the frontoparallel plane. For lines that were oriented in stereoscopic depth, errors rose to around 10%. McKee et al. measured the minimum detectable change in line length for lines oriented similarly to those in the Norman et al. study. The results were broadly similar: a twofold increase in error for the 3D-oriented lines compared with lines oriented in the frontoparallel plane.

For the experimental conditions in the present study, where no GFOV manipulation was involved, line-matching errors in the frontoparallel plane were around 5% (0° target elevation) and those for depth-oriented lines were around 10% (average of ±45° and ±90° target elevations in the veridical GFOV condition).

Figure 4 shows the effect of GFOV manipulation to be one of increasing overestimation as GFOV departs from the veridical angle. This effect is largest in the 100° GFOV condition and is consistent over the ±45° and the ±90° (Figure 5) target-elevation conditions. Overestimation errors with increasing GFOV were found by McGreevy and Ellis (1986) but not by Rosenberg and Barfield (1995), who found no effect of GFOV on their dependent measure.

The results of those two studies have, in part, been replicated in the present study. The GFOV difference between the parallel GFOV and the veridical GFOV conditions was 13.86°. We found no significant difference between these two conditions for all target elevations, similar to the results of Rosenberg and Barfield

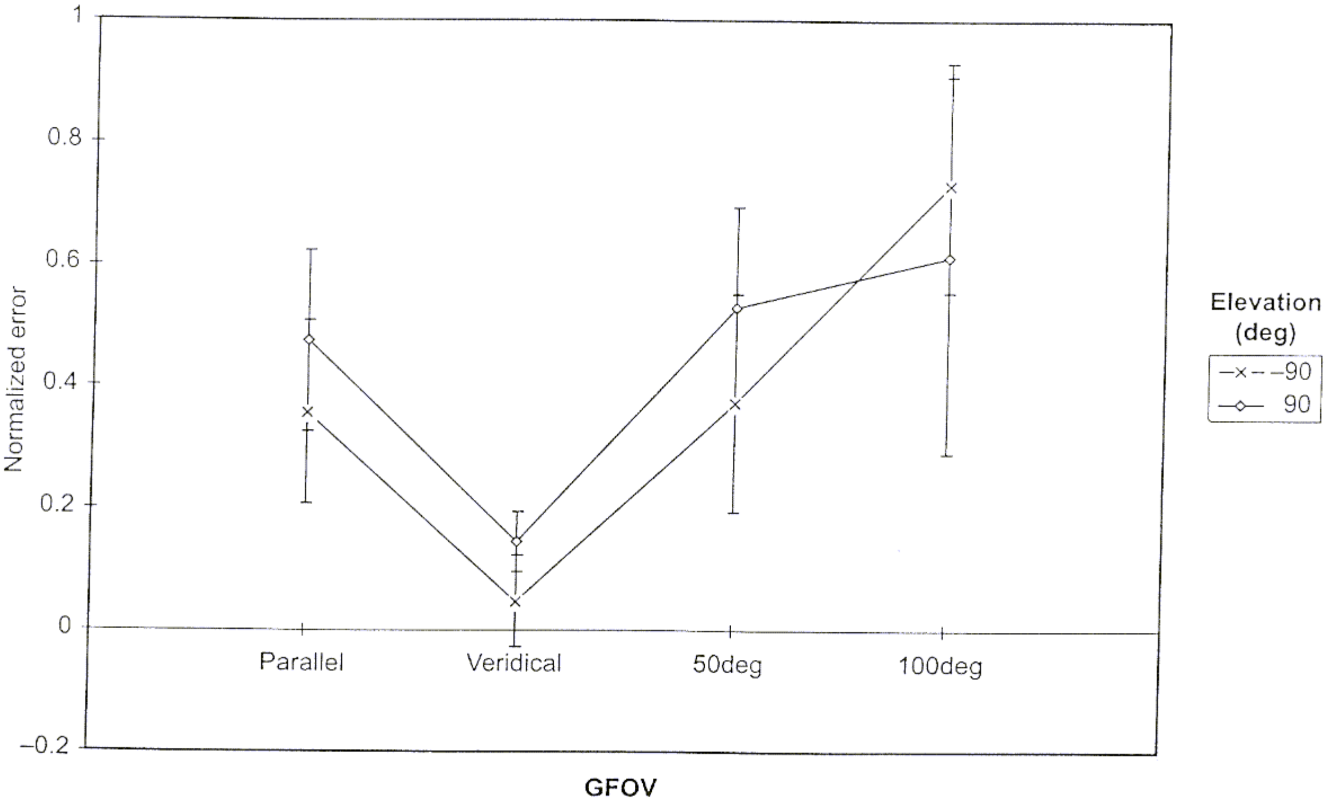

Figure 5. Effect of GFOV on radial distance matching error for ±90° elevations.

(1995). For the veridical GFOV, the 50° GFOV and the 100° GFOV conditions, which differed by greater amounts (40°– 90°), significant differences in length-matching errors were obtained, similar to the results of McGreevy and Ellis (1986). These results suggest that the lack of an effect of GFOV in Rosenberg and Barfield's study may have been attributable to the difference between the display FOV and their GFOV conditions being too small.

The present experiment found an increase in overestimation of target elevation angle at larger GFOVs. This result contradicts that of McGreevy and Ellis (1986), who found that overestimation of target elevation angle was reduced at larger GFOVs. An explanation for this may be that the present experiment is not directly comparable with that of McGreevy and Ellis. Of the several differences between the two studies (e.g., the use of distance-matching error as the dependent variable, the viewpoint elevation of 90°, and the use of a stereoscopic rather than a monoscopic display), we believe that the key difference is the viewpoint elevation.

McGreevy and Ellis (1986) used a viewpoint elevation of 22°; hence the depth compression produced by the perspective projection affected both elevation and azimuth dimensions. Moreover, the viewpoint elevation being less than 45° implies that the perspective compression effect should be more pronounced in the azimuth dimension (Hendrix & Barfield, 1997). McGreevy & Ellis's (1986) azimuth data show sinusoidal error variation, the amplitude of which varies as a function of GFOV. The minimum azimuthal error amplitude occurred in the 60° GFOV condition, and there is evidence (see Figure 9 in McGreevy & Ellis, 1986) that the azimuthal error amplitude in their study increased in the 30° and 120° GFOV conditions. In the present study, given that the perspective compression effect occurs entirely within the elevation dimension, it is tempting to compare the effect of elevation error across GFOVs with the azimuth error across GFOVs found by McGreevy and Ellis. The implication of this comparison is that similar results obtain in both studies: deviations of display GFOV away from the veridical increase error in the perspective-compressed dimension or dimensions.

CONCLUSION

The present experiment investigated the effect on distance-matching performance for the perspective parameter of GFOV within a stereoscopic display. Of particular interest was whether or not the depth cue of linear perspective is necessary in a plan-position display employing stereoscopic imagery.

The minimum distance-matching error occurred in the veridical projection condition and as GFOV was increased away from the veridical angle, distance-matching error was found to increase. Statistically speaking, the present study found no difference in performance between the parallel projection condition and the veridical perspective projection condition. However, there was a trend in the data toward greater errors in the parallel projection condition. This trend suggests that in the absence of other factors, a veridical perspective projection display should produce more accurate performance than a parallel projection display.

Consistent with previous studies (McGreevy & Ellis, 1986; Rosenberg & Barfield, 1995), the present study found that relatively large departures of GFOV from the veridical are required to produce an effect on performance. This would indicate that although the veridical projection format is optimum, variations in GFOV from the veridical of the order of 10° to 20° may well be tolerated.

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Peter Banton is a research fellow at the University of York, England, where he received his Ph.D. in experimental psychology in 1998.

Peter Thompson is a senior lecturer in psychology at the University of York, England. He received his Ph.D. in experimental psychology from the University of Cambridge, England, in 1976.

Philip T. Quinlan is a lecturer at the University of York, England. He received his Ph.D. in experimental psychology from Birkbeck College, University of London, England, in 1988.

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