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Using Relative Position and Temporal Judgments to Identify Biases in Spatial Awareness for Synthetic Vision Systems

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Synthetic vision systems (SVS) are cockpit displays that depict terrain ahead of ownship to prevent controlled flight into terrain. This work investigated how spatial biases manifest themselves in SVS displays. Eighteen pilots made spatial judgments (relative angle, distance, height, and abeam time) regarding the location of terrain points displayed in 112 5-sec videos of SVS displays. Judgment error characterized spatial biases related to between-map scale differences in geometric field of view, within-map differences in distance, within-map differences in orientation, the virtual space effect, the filled distance effect, and time. Recommendations for future experimentation and modeling are made.

Controlled flight into terrain (CFIT), where a fully functional aircraft is inadvertently flown into the ground, water, or other terrain obstacle, has been the cause of more than 24% of all fatal accidents in worldwide commercial aviation since 1987, resulting in a loss of 3,735 lives and making it the largest source of fatalities in commercial aviation (Boeing Commercial Airplanes, 2006). CFIT accidents are characterized by a loss of situation awareness (SA) in low-level flight and low-visibility conditions (Khatwa & Roelen, 1999).

Synthetic vision systems (SVS) are technologies that combat this problem. By using onboard terrain and obstacle databases and global positioning system (GPS) data, SVS displays enhance pilot spatial awareness by creating a synthetic, clear-

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day view of the world surrounding ownship regardless of the actual visibility conditions (Arthur, Prinzel, Kramer, Parrish, & Bailey, 2004).

SPATIAL AWARENESS AND SPATIAL BIASES

Spatial awareness can be defined as the extent to which a pilot notices objects in the surrounding environment (Level 1), the pilot's understanding of where these objects are with respect to ownship (Level 2), and the pilot's understanding of where these objects will be relative to ownship in the future (Level 3; Wickens, 2002). This aspect of SA is relevant to SVS because it encompasses a pilot's knowledge about the relative position of terrain.

SVS head-down displays are two-dimensional (2D) perspective displays. Such displays attempt to convey three-dimensional (3D) spatial information using a 2D image. The angular boundaries of the pyramidal 3D space represented by one of these displays are defined by a geometric field of view (GFOV) radiating out from a station point (FIGURE 1). The perspective display itself is a 2D image created by projecting the 3D volume of space onto an intersecting plane (the projected 2D image).

Because SVS are 2D perspective displays, spatial awareness can be impacted by spatial biases commonly associated with this type of display (Wickens, 2002). One category of biases are associated with the 3D-to-2D projection effect, where viewer magnitude judgments of spatial quantities depicted in a 3D scene will be influenced by the magnitude of its 2D projection in the 2D image (McGreevy, Ratzlaff, & Ellis, 1985). McGreevy and Ellis (1986) used this bias to partially explain participant overestimation of elevation direction (elevation angle) judgments and a sinusoidal pattern in over- and underestimation in azimuth angle judgments

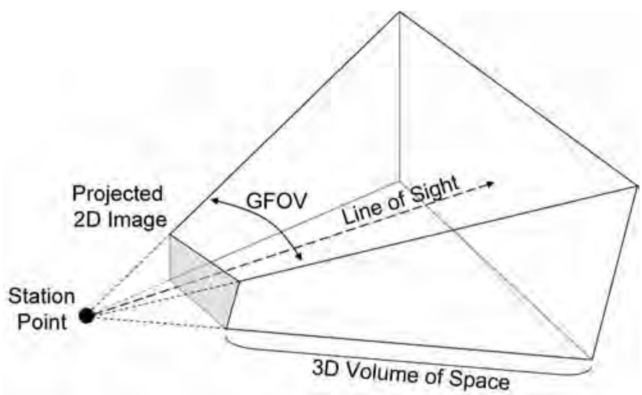

FIGURE 1 A perspective display. (See http://cog.sys.virginia.edu/SVS/figure1.png)

between two objects in a perspective display. This concept can be related to more general biases based on the concept of resolution: People will tend to decrease spatial estimates of spatial quantities as the amount of screen space used to represent that quantity (its 2D projection) decreases (Wickens, 2002). These relate to all of the following spatial biases:

- *Between-map scale differences in GFOV (FIGURE 2a).* Increasing the GFOV of a display (without changing the size of the display) increases the amount of 3D space represented in the display. Because more spatial information must now be represented on the 2D image, the display resolution used to represent spatial quantities decreases. Thus, with a 2D perspective display, the magnitude of viewer-perceived spatial quantities will decrease with an increase in GFOV (Barfield, Rosenberg, & Furness, 1995; Wickens, 2002).
- *Within-map differences in orientation (FIGURE 2b)*. In perspective displays, the amount of resolution used to represent a 3D distance from the station point in the 2D image will decrease as the distance aligns with the display's line of sight. Thus, with a 2D perspective display, viewer estimates of distance magnitudes will be smaller for distances that are more closely aligned with the displays line of sight than equivalent distances that are more perpendicular to it (Wickens, 2002; Wickens, Liang, Prevett, & Olmos, 1996).
- *Within-map differences in distances (FIGURE 2c)*. Because the amount of 3D space represented in a 2D perspective display increases as the distance from the station point increases, the amount of resolution used to depict 3D spatial quantities in the projected 2D image decreases as its distance from the station point increases. Thus, with a 2D perspective display, viewers will judge spatial quantities that are further from the station point as being smaller than equivalent quantities that are closer. Further, because projections of 3D distances from the station point decrease in resolution as the magnitude of the distance increase, viewers underestimate further distances as compared to closer one (Wickens, 2002).

Spatial awareness can be further biased by what is known as the virtual space effect (FIGURE 2d; McGreevy & Ellis, 1986; McGreevy et al., 1985). When a person views a display, an angle is formed between the edges of the display and the viewer's eyes called the eye field of view (EFOV). The virtual space effect occurs because of what McGreevy and Ellis (1986) called the "window assumption," where the viewer assumes his or her eyes are at the display's station point and thus that spatial information derived from the display can be treated as if it were being observed through an equally sized window (the viewer assumes GFOV ≠ EFOV). However, the perception of spatial quantities is distorted when GFOV / EFOV. When the viewer's eyes are further from the display than the station point, the GFOV is greater than the EFOV (GFOV > EFOV). This causes the viewer to inter-

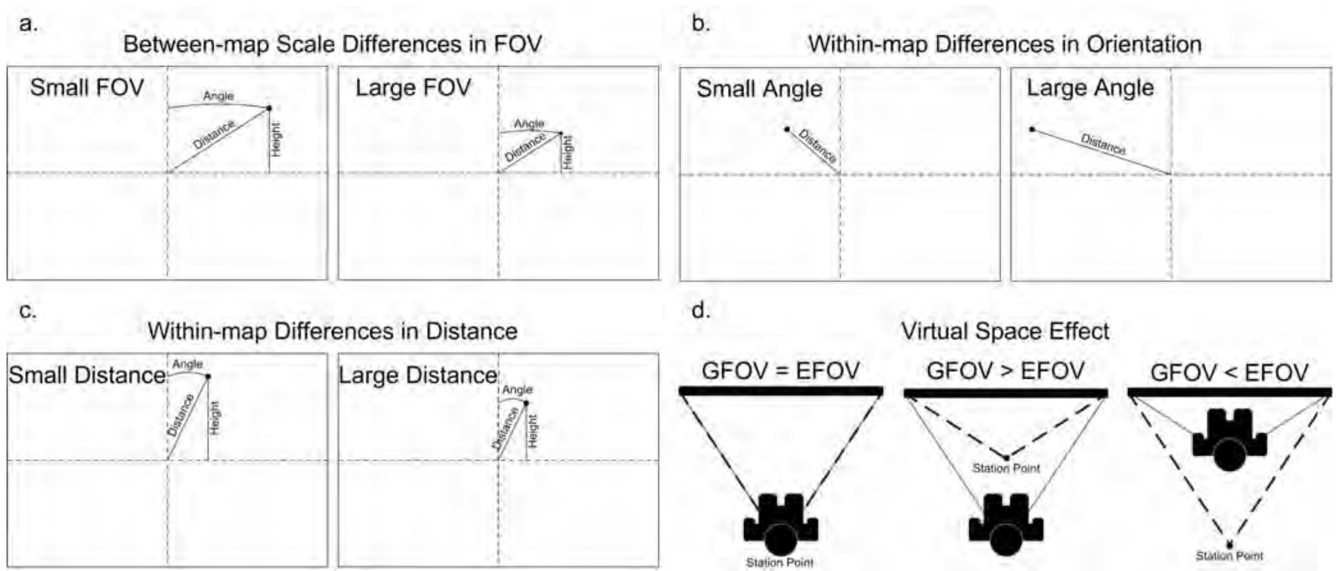

FIGURE 2 Illustration of 2D perspective display spatial biases. Panels a, b, and c depict a perspective displays with a point (a black dot) at a relative 3D positions to the display's station point. The line of site in the displays of a, b, and c are indicated by the intersection of the two dotted lines. (a) For two points with the same relative 3D position to the display's station point, the relative azimuth angle, distance, and height of the point on the display with the larger GFOV is displayed with less resolution than on the display with the smaller GFOV. (b) For two points with the same relative distance and height to the station point, the relative distance of the point with the small relative azimuth angle will be displayed with less resolution than the point with the larger relative angle. (c) For two points with the same relative azimuth angle and height to the station point, the point with the large distance will have its relative distance, height, and angle displayed with less resolution than the point with the small distance. (d) When the viewer's eyes are at the station point, GFOV = EFOV. When the viewer's eyes are further from the display than the station point, GFOV > EFOV. When the viewer's eyes are closer to the display than the station point, GFOV < EFOV. (See http://cog.sys.virginia.edu/SVS/figure2.png)

pret objects as being closer together than they actually are. When the viewer's eyes are closer to the display than the station point, the GFOV is less than the EFOV (GFOV < EFOV). This causes the viewer to interpret objects as being further apart than they actually are. The effect of these biases is directly proportional to the difference in magnitude between the GFOV and the EFOV.

There are also display-independent spatial biasing factors that may distort spatial perception with 2D perspective displays. One such bias is the filled distance effect. The filled distance effect asserts that people will amplify estimates of a spatial quantity as the amount of data encoded in that space increases (Wickens, 1992, 2002).

Another of these biases occurs with respect to time. When motion is being perceived, time-to-contact judgment has been theorized as being a derived quantity (distance divided by velocity). If true, people may bias these judgments in favor of perceived distance because distance is cognitively easier to estimate than velocity (Wickens, 2002). Thus, because perceived distance can be biased by perspective displays, and time-to-contact judgment can be biased by perception of distance, time-to-contact judgments may be biased by perspective displays.

MEASURING SPATIAL AWARENESS

In SVS and related research, performance measures include cross-track error (Alexander, Wickens, & Hardy, 2005), the number of correct identifications made when matching video of actual terrain to SVS displays (Schnell & Lemos, 2002), ordinal distance judgments (Yeh, 1992), and azimuth and elevation angle judgments of the relative position of two objects over synthetic terrain (Alm, Lif, & Öberg, 2003; Barfield & Rosenberg, 1995; McGreevy & Ellis, 1986). Subjective awareness measures have also been used in SVS research, including the Situation Awareness Rating Technique (SART; Hughes & Takallu, 2002), Situation Awareness–Subjective Workload Dominance (SA–SWORD; Arthur et al., 2004; Hughes & Takallu, 2002), and terrain awareness (Bailey, Parrish, Arthur, & Norman, 2002; Glaab & Hughes, 2003).

None of the measures used in these experiments directly probe the pilot's knowledge of all three levels of spatial awareness. Thus, they are not appropriate for evaluating how spatial biases manifest themselves with respect to ownship in SVS displays. The only exception is a study in which pilots were asked to reproduce the location of highlighted terrain points from blanked SVS primary flight displays on a 180° outside world conformal (GFOV = EFOV) display during pauses in flight simulation experiments (Alexander et al., 2005). In this experiment, participants were presented with four display conditions based on two display sizes (large or small) and two GFOVs (30° and 60°). Of these configurations, only one was conformal (the large display with the 30° GFOV). The GFOV of the other display configurations was larger than the EFOV, with the greatest discrepancy occurring for the 60° GFOV displays.

Participants tended to estimate the location of the terrain points as being closer to their line of sight than they actually were. These results can be attributed to the virtual space effect given that three of the four SVS display conditions had GFOVs that were greater than the EFOV (the exception was conformal). However, it was also found that the magnitude of this bias was significantly greater for the 30° GFOV displays than the 60° GFOV displays. This is not what would be expected given the biases associated with between-map scale differences in GFOV.

Objectives

The results reported herein were part of a larger study designed to evaluate new judgment-based measures of spatial awareness for SVS. Participants provided relative (azimuth) angle, relative distance, relative height, and abeam time judgments about the relative location (to ownship) of a point shown on SVS terrain during short noninteractive simulations. Identifying the terrain point probed Level 1 spatial awareness. The relative angle, distance, and height judgments probed Level 2 spatial awareness (the relative location of the terrain). The abeam time judgments probed Level 3 spatial awareness (the terrain's relative location in the future). A main focus of the larger study was to evaluate the relative spatial awareness provided by different textures and GFOVs (Bolton, Bass, & Comstock, 2007). Additionally, the performance of these measures has also been compared with subjective measures commonly used to assess spatial awareness and SA for SVS (Bolton & Bass, 2007).

Because the experimental design provided controls to account for potential spatial awareness biases, and because the new spatial awareness measures probe pilot comprehension of four different spatial dimensions (angle, distance, height, and time), this work experimentally investigation the spatial biases Wickens (2002) predicted would manifest themselves in SVS head-down displays. Because the majority of these biases had not been explicitly observed in SVS, this work strived to identify which, if any, of these biases were actually present in SVS displays. For biases identified as being present, this work aspired to qualify their importance as they related to SVS design decisions and training practices.

METHODS

Participants

Eighteen general aviation pilots volunteered for the study. All participants had less than 400 hr of flight experience ($M = 157$, $SD = 75$). They were familiar with the out-the-window view from a cockpit but not with SVS displays. They were each paid $100 for their participation.

Apparatus

Experiments were run in a windowless, constantly lighted laboratory. Workstations displayed each simulation and collected participant judgments. Simulations depicted SVS head-down displays with the symbology shown in FIGURE 3. In simulations, the location of the terrain point was indicated using a yellow inverted cone (d = 500 ft, h = 500 ft) rendered as part of the SVS environment. The tip of the cone intersected the terrain at the terrain point. All simulations depicted SVS displays in straight, level flight (no pitch or roll) at 127 kt with no additional influences on motion. They were displayed as 5-sec, 836 × 728 pixel, 30 frames per second Windows Media Video (WMV) files. Custom software played the WMV files and collected participant responses (Bolton, Bass, & Comstock, 2006).

Independent Variables

There were five within-subjects independent variables. These included texture, GFOV, and three scenario geometry variables: the relative (azimuth) angle, relative distance, and relative height of the terrain point to ownship. Seven textures (FIGURE 4) and two GFOVs (30° and 60°) were used in the SVS displays.

The location of the terrain point varied based on its relative position to ownship at the end (last frame) of a simulation by changing the three scenario geometry parameters: the relative angle, distance, and height of the terrain point with respect to ownship. Each of the variables had two levels (Table 1).

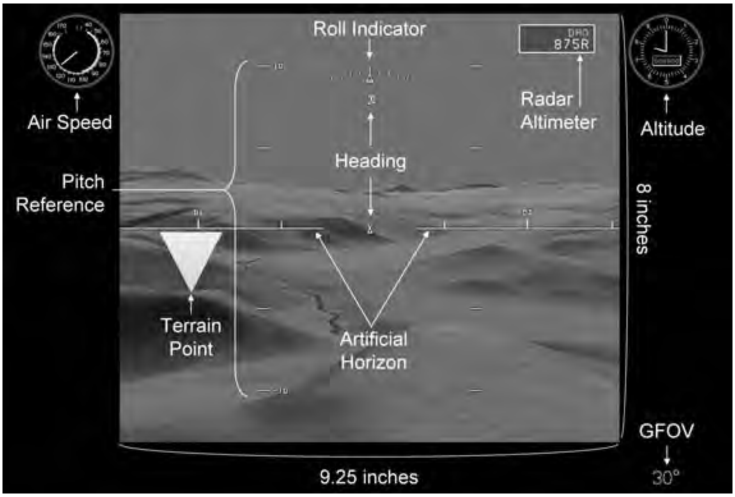

FIGURE 3 The SVS display and symbology used in the experiment (labels added). SVS displays were presented to participants with an eye distance of approximately 30 in. and an EFOV of approximately 18°. (See http://cog.sys.virginia.edu/SVS/figure3.jpg)

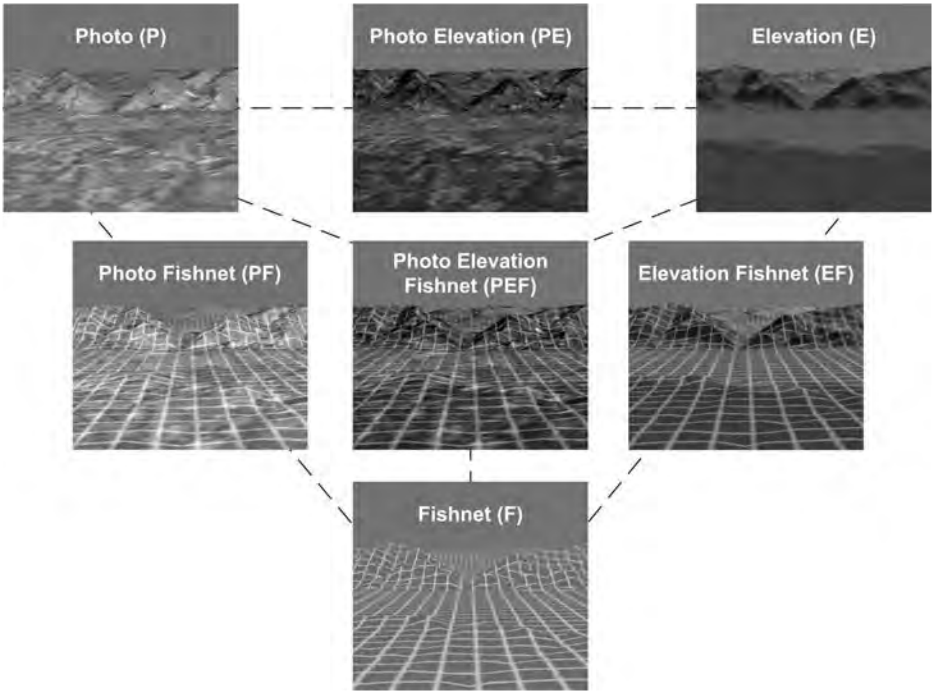

FIGURE 4 The terrain textures evaluated in the experiment (labels added). (See http://cog.sys.virginia.edu/SVS/figure4.jpg)

TABLE 1
Terrain Point Relative Position to Ownship (Scenario Geometry)
Level Encoding

Variable	*Range*	*Distribution*	*Level*
Relative (azimuth) angle	[0°, 6.5°]	$N(\mu = 3.75, s = 1.25)$	Small
	[8.5°, 15°]	$N(\mu = 11.25, s = 1.25)$	Large
Relative distance	[1 nm, 3.25 nm]	$N(\mu = 2.25, s = 0.417)$	Near
	[3.75 nm, 6 nm]	$N(\mu= 4.75, s = 0.417)$	Far
Relative height	[–1,000 ft, –100 ft]	U(–1,000, –100)	Below
	[100 ft, 1,000 ft]	U(100, 1,000)	Above

Dependent Measures

Directional error-dependent measures were calculated from the four judgment values: relative angle (°), relative distance (nmi), relative height (ft), and abeam time (sec; see Table 2). Directional error for the abeam point (the point of closest approach to the terrain point) position (nmi) was calculated using the abeam point

TABLE 2
Dependent Measure Formulations

Variable	*Actual Value*	*Judgment Value*	*Directional Judgment Error*
Relative angle	A_a	A_j	$A_e = \begin{cases} A_j - A_a & \text{if } A_a > 0 \\ -A_j + A_a & \text{otherwise} \end{cases}$
Relative distance	D_a	D_j	$D_e = D_j - D_a$
Relative height	H_a	H_j	$H_e = \begin{cases} H_j - H_a & \text{if } H_a > 0 \\ -H_j + H_a & \text{otherwise} \end{cases}$
Abeam time	τ_a	τ_j	$\tau_e = \tau_j - \tau_a$
Abeam point distance	$P_a = D_a \times \cos(\lvert A_a \rvert)$	$P_j = D_j \times \cos(\lvert A_j \rvert)$	$P_e = P_j - P_a$

Note A_a and A_j were measured relative to the aircraft's vector of displacement with angles in the clockwise direction being positive and angles in the counterclockwise direction being negative. H_a and H_j were measured relative to the aircraft's height with positive heights above the aircraft and negative heights below.

position associated with user relative angle and distance judgments (Table 2). Each directional error term represented both the direction and magnitude of the error in the judgment value. When a participant overestimated a judgment, the corresponding directional error term was positive. When the participant underestimated a judgment, it was negative.

Hypotheses

Hypothesis 1: Participants would underestimate relative angle, distance, and height judgments for the 60° GFOV as compared with the 30° GFOV. Equal relative angle, distance, and height values are represented with less resolution in displays utilizing a 60° GFOV than displays utilizing a 30° GFOV because of the between-map scale differences in GFOV (Wickens, 2002). This suggested that participants would underestimate position judgments for the 60° GFOV as compared to the 30° GFOV.

Hypothesis 2: Participants would underestimate distance judgments for small relative angles as compared to large ones. Terrain points with small angles are closer to the observer's line of sight than points with large angles. Thus, due to the within-map differences in orientation present in SVS displays, the relative distance of the terrain points with smaller relative angles is represented with less resolution than terrain points with large angles (Wickens, 2002). This suggested that participants would make smaller relative distance judgments for small angles than for large ones.

Hypothesis 3: Participants would underestimate relative angle, distance, and height judgments for far distances as compared to near ones. Because of the within-map differences in distance present in SVS displays, relative angles, distances, and heights are represented with less resolution for far distances than they are for near distances (Wickens, 2002). This suggested that relative height and distance judgments would be underestimated for far distances as compared with near ones.

Hypothesis 4: Participants would underestimate relative angle judgments and underestimate them more for the 60° FOV. Because the two GFOVs (30° and 60°) used in this experiment were larger than the EFOV (18°), participants were expected to underestimate relative angle judgments due to the virtual space effect (a bias compatible with the results found by Alexander et al., 2005). Because the discrepancy between the EFOV was greater for the 60° GFOV than the 30° GFOV, participants were expected to underestimate relative angle judgments more for the 60° GFOV.

Hypothesis 5: Participants would overestimate relative angle judgments for points below the aircraft compared to points above the aircraft. The screen space used to represent the relative angle of a point below the aircraft will likely contain more terrain information than the screen space used to represent an equivalent relative angle for a point above the aircraft (which will contain more sky). Thus, because the filled distance effect predicts a magnification of a spatial quantity's magnitude as the amount of data encoded in that space increases (Wickens, 2002), participants were expected to magnify relative angles for points below the aircraft.

Hypothesis 6: Participants' directional time error will be directly proportional to their directional abeam point distance error. The abeam time judgment can be viewed as a judgment of time-to-contact to the abeam point. Thus, because time-to-contact judgments are assumed to be derived from perceived relative distance and velocity (time = distance / velocity), with distance being cognitively easier to estimate (Wickens, 2002), τ_e will be positively correlated with P_e.

Procedure

Each experimental session lasted less than 4 hr. The participants completed consent forms and were briefed about the experiment. For each trial, participants viewed 5-sec simulations of an SVS head-down display in flight (FIGURE 3). At the end of the 5 sec, the simulation paused for 1 sec, and the screen was cleared.

Each simulation (representing a unique combination of within-subjects variable levels) depicted a unique terrain configuration.

For each trial, participants made four judgments based on the relative position of the terrain point: relative angle, relative distance, relative height, and abeam time using the interface in FIGURE 5. For the relative distance and angle judgments, participants placed a yellow X in the upper left section of the display corresponding to the lateral location of the terrain point relative to the aircraft. Values for relative angle (°) and distance (nm) were displayed next to the X. For the relative height judgment, the participant placed a yellow X on a vertical scale in the upper right of the display corresponding to the relative height of the terrain point. The relative height was displayed in feet next to the X as it was moved. For the abeam time judgment, participants entered the time judgments in minutes and seconds using the keyboard. To support this time judgment, a yellow dot on the relative distance and angle judgment collection interface indicated the location of the abeam point based on the relative distance and angle judgment. Participants were asked to

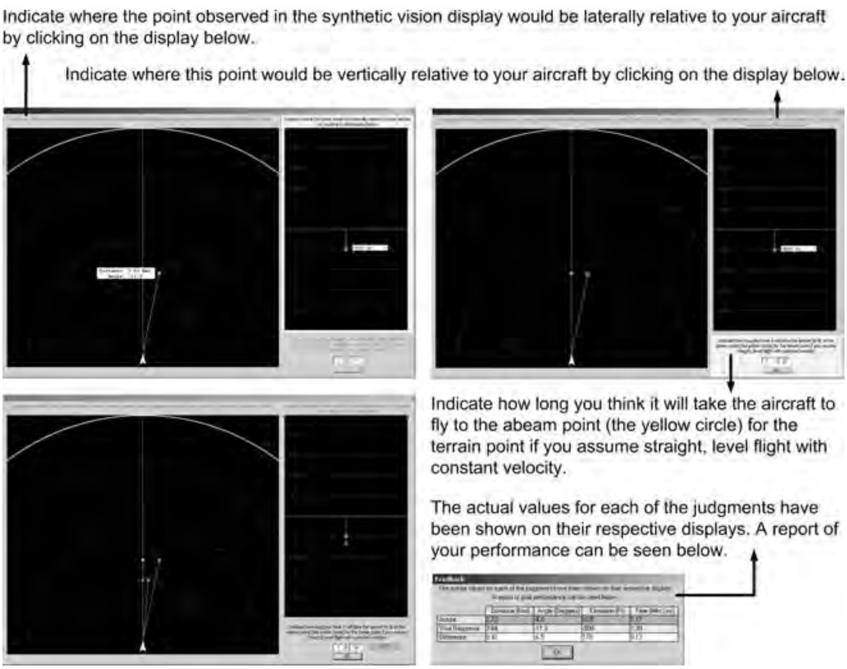

FIGURE 5 The judgment collection interface in multiple modes of operation (clockwise from the upper left): the relative distance, angle, and height judgments; the abeam time judgment; training feedback on the judgment collection interface; numerical training feedback shown concurrently with feedback on the judgment collection interface. (See http://cog.sys.virginia.edu/SVS/figure5.png)

perform these tasks as quickly and accurately as possible. For training trials, participants were given feedback relating to the accuracy of their judgments (see Bolton et al., 2006, for more information about the experimental apparatus).

Each participant experienced 112 counterbalanced experimental trials (7 textures × 2 GFOVs × 2 relative angles × 2 relative distances × 2 relative heights = 112) and 72 training trials. Participants saw all of the trials with one GFOV before seeing any trials with the other. GFOV presentation order was counterbalanced between participants. Textures used to derive other textures always appeared before their derivatives to avoid complications associated with presenting a derivative texture before participants had seen its bases. Each participant saw two of the base textures, the combination of them, the third texture, and the rest of the combinations. Three texture orders were created so that no base texture was introduced in more than one ordered slot: {P, E, PE, F, PF, EF, PEF}, {E, F, EF, P, PE, PF, PEF}, and {F, P, PF, E, EF, PE, PEF}. Texture orders were counterbalanced between participants.

For the first texture seen for the first GFOV, there were 12 training trials. For the other six textures, there were four training trials per texture (4 × 6 = 24). This pattern was repeated for the second GFOV. Thus, there were 12 + (4 × 6) = 36 training trials for each GFOV for a total of 2 × 36 = 72 training trials. Participants received judgment accuracy feedback after each training trial (see FIGURE 5).

The order in which the eight scenario geometry levels were presented was unique for each texture and FOV combination. Thus there were 14 scenario geometry presentation orders. Scenario geometry variable levels were counterbalanced between presentation orders so that each combination of variable levels appeared in each ordered slot twice and directly followed every other combination twice.

On completion of all of the trials for each texture for each GFOV, subjective demand (Taylor, 1990), awareness (Glaab & Hughes, 2003), and clutter (Bailey, Kramer, & Prinzel, 2006) ratings were collected using 100-point Likert scales. After all of the trials for a GFOV were completed, participants made SA-SWORD (Vidulich & Hughes, 1991) pairwise comparisons between each texture seen with that GFOV (for more detail, see Bolton & Bass, 2007).

Experimental Design and Data Analysis

The experiment employed a repeated measures design with 18 participants. Three participants were randomly assigned to each of the six combinations of the GFOV and texture orders (2 GFOV orders × 3 texture orders = 6).

The directional bias of a given judgment was assessed using a two-tailed *t* test comparing the mean directional error to zero. The main and two-way interaction effects of the within- and between-subject factors on the dependent measures were assessed using univariate repeated measures analyses of variance (ANOVAs) with a Type III sum of squares (Brace, Kemp, & Snelgar, 2003). A Tukey's post-hoc analysis was used to identify significant differences between the levels of the interaction effects (Stevens, 2002). A Pearson's correlation coefficient was used to assess whether τ_e was correlated with P_e.

RESULTS

Results for the main and interaction effects are reported using $\alpha = .05$ for significance (Table 3). For the ANOVAs, differences between levels of significant main and interaction effects (including post-hoc results) can be seen in Figures 6 through 9.

Directional Angle Error (A_e)

On average, participants overestimated relative angle judgments ($M = 2.53°$, $t = 21.73$, $p < .01$). Distance, height, and GFOV were all significant main effects for A_e (Table 3). An examination of differences between their levels (FIGURE 6) revealed that participants overestimated angles more for points with near distances, points below the aircraft, and with 30° GFOV displays.

TABLE 3
Significant Main and Interaction Effects for Directional Error

Independent Var.	A_e	D_e	H_e	τ_e
Angle	$F(1, 17) = 1.88$ $p = .19$	$F(1, 17) = 0.01$ $p = .93$	$F(1, 17) = 14.16$ $p < .01$*	$F(1, 17) = 0.63$ $p = .44$
Distance	$F(1, 17) = 12.37$ $p < .01$*	$F(1, 17) = 83.08$ $p < .01$*	$F(1, 17) = 126.22$ $p < .01$*	$F(1, 17) = 78.8$ $p < .01$*
Height	$F(1, 17) = 12.6$ $p < .01$*	$F(1, 17) = 3.97$ $p = .06$	$F(1, 17) = 0.60$ $p = .45$	$F(1, 17) = 4.46$ $p = .05$*
GFOV	$F(1, 17) = 5.63$ $p = .03$*	$F(1, 17) = 3.30$ $p = .09$	$F(1, 17) = 5.87$ $p = .03$*	$F(1, 17) = 1.16$ $p = .30$
Angle × Distance	$F(1, 17) = 0.01$ $p = .93$	$F(1, 17) = 0.86$ $p = .37$	$F(1, 17) = 10.64$ $p < .01$*	$F(1, 17) = 0.02$ $p = .89$
Angle × Height	$F(1, 17) = 4.88$ $p = .04$*	$F(1, 17) = 7.87$ $p = .01$*	$F(1, 17) = 2.35$ $p = .14$	$F(1, 17) = 10.51$ $p < .01$*
Angle × GFOV	$F(1, 17) = 4.80$ $p = .04$*	$F(1, 17) = 8.43$ $p = .01$*	$F(1, 17) = 20.38$ $p < .01$*	$F(1, 17) = 17.39$ $p < .01$*
Distance × Height	$F(1, 17) = 0.00$ $p = .98$	$F(1, 17) = 2.13$ $p = .16$	$F(1, 17) = 0.06$ $p = .81$	$F(1, 17) = 0.46$ $p = .51$
htDistance × GFOV	$F(1, 17) = 0.60$ $p = .45$	$F(1, 17) = 1.20$ $p = .29$	$F(1, 17) = 16.65$ $p < .01$*	$F(1, 17) = 1.02$ $p = .33$
Height × GFOV	$F(1, 17) = 0.01$ $p = .93$	$F(1, 17) = 1.04$ $p = .32$	$F(1, 17) = 0.00$ $p = .99$	$F(1, 17) = 0.05$ $p = .83$

Note. GFOV = geometric field of view.
*$p < .05$.

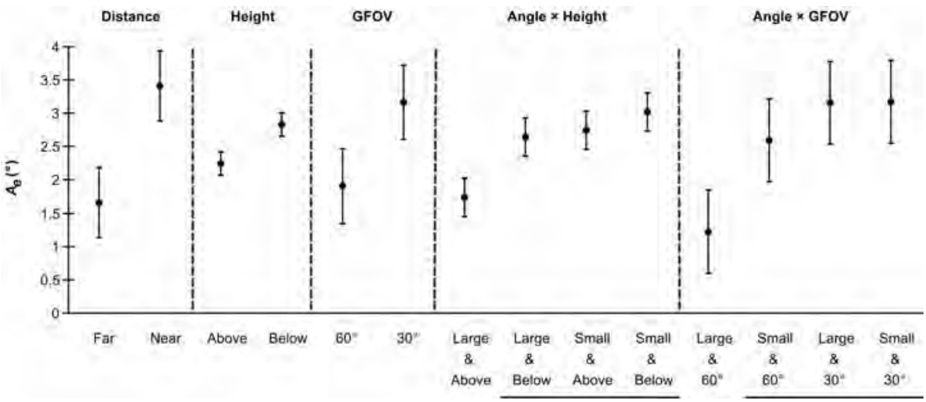

FIGURE 6 Plots of main and interaction effects that were significant for A_e. Filled circles indicate means. Bars around means indicate Tukey's intervals from a Tukey's honestly significant difference (HSD) with $\alpha = .05$. Lines under variable levels indicate homogeneous subsets (where no significant differences in error were observed between variable levels) as indicated by the Tukey's HSD. (See http://cog.sys.virginia.edu/SVS/figure6.png)

Angle × Height and Angle × GFOV were both significant interaction effects for A_e (Table 3). Post-hoc analyses revealed that, for the Angle × Height interaction, participants overestimated relative angle judgments least for points with large angles that were above the aircraft. For the Angle × GFOV interaction, participants overestimated angles least for points with large angles on 60° GFOV displays (FIGURE 6).

Directional Distance Error (D_e)

Participants, on average, did not overestimate or underestimate relative distances. However, significant differences were found between levels of the relative distance main effect. Participants underestimated relative distances for points with far distances and overestimated them for points were near distances.

Post-hoc analyses were used to evaluate the differences between the levels of the two significant interaction effects (FIGURE 7). For the Angle × Height interaction, participants underestimated distances for points below the aircraft and overestimated them for points above the aircraft. However, there was no significant difference between points with small relative angles below the aircraft and points with small relative angles above the aircraft. The analysis of the Angle × GFOV interaction only showed significant differences between GFOVs with participants underestimating distances for the 30° GFOV and overestimating them for the 60° GFOV.

Directional Height Error (H_e)

Participants underestimated relative height judgments ($M = -81.62$ ft, $t = -11.29$, $p < .01$). Significant main effects were observed for angle, distance, and GFOV

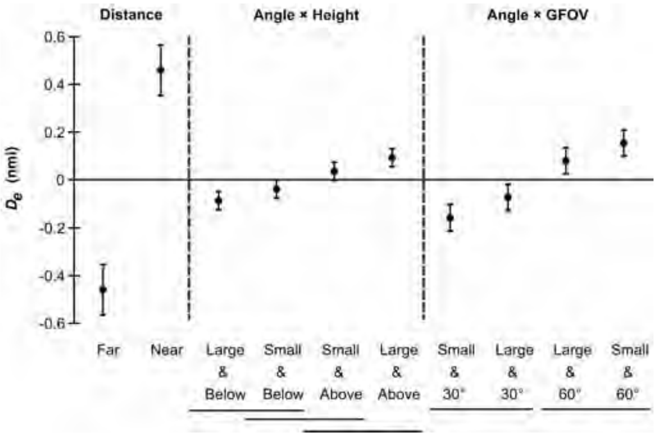

FIGURE 7 Plots of main and interaction effects that were significant for D_e. Filled circles indicate means. Bars around means indicate Tukey's intervals from a Tukey's honestly significant difference (HSD) with α =.05. Lines under variable levels indicate homogeneous subsets (where no significant differences in error were observed between variable levels) as indicated by the Tukey's HSD. (See http://cog.sys.virginia.edu/SVS/figure7.png)

(Table 3), where participants underestimated heights significantly more for points with small angles, points with far distances, and for displays with the 60° GFOV.

A post-hoc analysis was used to evaluate the levels of the significant interaction effects (FIGURE 8). For the Angle × Distance interaction, participants underestimated relative heights most for points with far distances (for both small and large

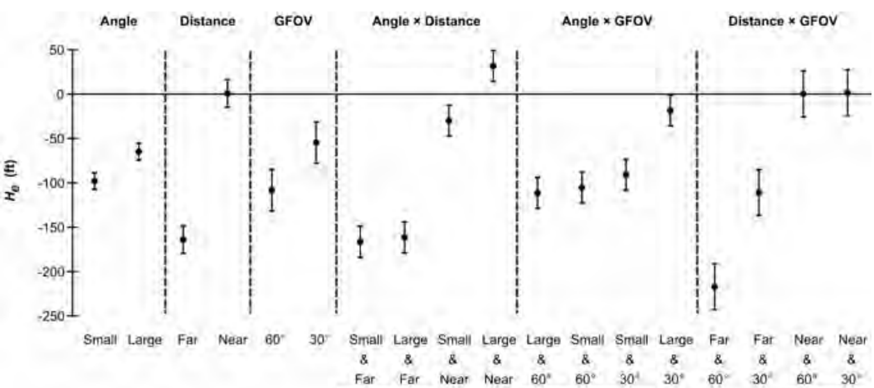

FIGURE 8 Plots of main and interaction effects that were significant for H_e. Filled circles indicate means. Bars around means indicate Tukey's intervals from a Tukey's honestly significant difference (HSD) with α =.05. Lines under variable levels indicate homogeneous subsets (where no significant differences in error were observed between variable levels) as indicated by the Tukey's HSD. (See http://cog.sys.virginia.edu/SVS/figure8.png)

distances), underestimated them significantly less for points with small angles and near distances, and overestimated them for points with large angles and near distances. For Angle × GFOV, participants understated heights significantly less for points with large distances and the 30° GFOV. In the Distance × GFOV interaction, participants underestimated heights the most for points with far distances on 60° GFOV displays, underestimated them significantly less for points with far distances on 30° GFOV displays, and with almost no bias (mean H_e near zero) for points with near distance on both 30° and 60° GFOV displays.

Directional Abeam Time Error (τ_e)

Participants underestimated relative time judgments ($M = -1.91$ sec, $t = -2.61$, $p < .01$). Both distance and height were significant main effects for τ_e (Table 3). Participants underestimated abeam times for points with far distances and overestimated them for points with near distances (FIGURE 9). They also underestimated abeam times for points below the aircraft but had no observable bias for points above the aircraft.

A post-hoc analysis of the significant interaction effects revealed that for the Angle × Height interaction, participants overestimated abeam times for points with large angles and underestimated them similarly for the other three factor levels (FIGURE 9). For the Angle × GFOV interaction, participants underestimated abeam times significantly more for points with small angles on 30° GFOV displays than for all the other factor levels; underestimated them least for points with large

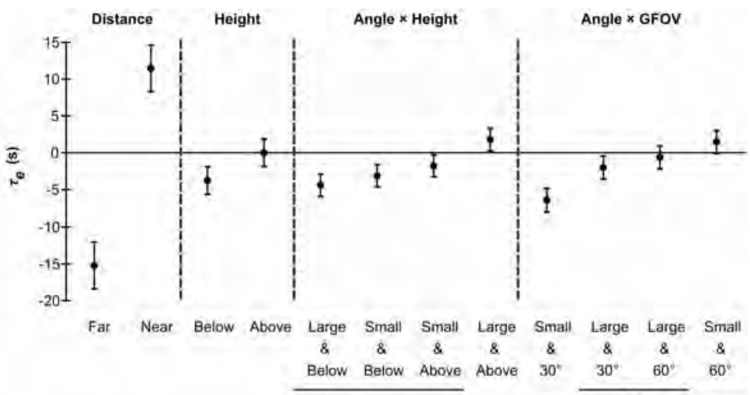

FIGURE 9 Plots of main and interaction effects that were significant for τ_e. Filled circles indicate means. Bars around means indicate Tukey's intervals from a Tukey's honestly significant difference (HSD) with $\alpha = .05$. Lines under variable levels indicate homogeneous subsets (where no significant differences in error were observed between variable levels) as indicated by the Tukey's HSD. (See http://cog.sys.virginia.edu/SVS/figure9.png)

angles regardless of the GFOV; and overestimated them for points with small angles on 60° GFOV displays.

A Pearson's correlation coefficient for P_e and τ_e was significant ($r = -.15$, $p < .01$).

DISCUSSION

This study was conducted to determine if known perspective display spatial awareness biasing factors manifest themselves in SVS displays. Thus, this study had several hypotheses related to these known spatial biases. However, because of the nature of the experiment, several other biases were also found. Both are discussed in this section.

Hypothesis 1

The fact that participants made smaller relative angle (FIGURE 6) and height (FIGURE 8) judgments for the 60° GFOV than for the 30° GFOV is consistent with Hypothesis 1 that participants would underestimate relative angle, distance, and height judgments for the 60° GFOV as compared with the 30° GFOV. Thus, unlike Alexander et al. (2005), this study found evidence of biases associated with between-map scale differences in GFOV in SVS displays.

However, the fact that participants underestimated distances for the 30° GFOV and underestimated them for the 60° GFOV in the Angle × GFOV interaction is seemingly contradictory to Hypothesis 1. This may have been caused by the use of the cylindrical cone to indicate the position of the terrain point. Because a 60° GFOV reduces the resolution used to represent spatial data, and because the cone is a 3D object in the display, it was represented with less resolution in a display using a 60° GFOV, making it appear smaller than with a 30° GFOV. Thus, the effect of the display's between-map scale differences in GFOV on the cone's familiar size depth cue (Goldstein, 2002) may have overridden this same bias's effect on relative distance perception.

Hypothesis 2

Because angle was not a significant effect for directional distance error, there is no evidence to support or contradict Hypothesis 2 (that participants would underestimate distance judgments for small relative angles as compared to large ones due to within-map differences in orientation). Although angle plays a role in both of D_e's interaction effects (Angle × Height and Angle × GFOV in FIGURE 7), each contain levels where participants both overestimated and underestimated distance for points with large angles.

Participants underestimated heights more for small angles than for large angles (FIGURE 8). This suggests that, although not hypothesized about, within-map differences in orientation may have biased relative height judgment. A potential explanation for this is that, for points with equivalent distances from the display's station point, points with small azimuth angles to the line of site will be further away from the 2D projection plane (the projected 2D image) than points with larger relative angles. Thus, the 2D projection of the relative heights for points with small relative angles will be represented with less resolution than those for points with large relative angles. This would imply that participants would underestimate relative heights for points with small relative angles as compared to points with large relative angles. The observed behavior is compatible with this hypothesis.

Hypothesis 3

Participants underestimated angles more for far distances than for near distances (FIGURE 6), underestimated relative distances for far distances and overestimated them for near distances (FIGURE 7), and underestimated relative heights more for far distances than for near distances (FIGURE 8). All three of these findings support Hypothesis 3 that participants would underestimate relative angle, distance, and height judgments for far distances as compared to near distances due to within-map differences in distance.

Additionally, the results indicate that participants' average underestimation of relative heights is predominantly due to their underestimation of heights for points with far distances. This can be seen not only in distance's main effect for H_e, but also in the Angle × Distance and Distance × GFOV interactions (FIGURE 8). In all three cases, participants underestimated relative heights for far distances and had nearly unbiased height judgments for near distances.

Hypothesis 4

The results indicating that participants overestimated their relative angle judgments (FIGURE 6) contradict the first part of Hypothesis 4 that participants would underestimate relative angle judgments due to the virtual space effect, a condition found by Alexander et al. (2005). However, participants overestimated relative angles significantly less for the 60° GFOV than the 30° GFOV. This confirms the second half of Hypothesis 4 that participants would underestimate relative angles for the 60° GFOV as compared to the 30° GFOV due to the increased impact of the virtual space effect (the increased discrepancy between the 60° GFOV and the EFOV). This would seem to indicate that although the virtual space effect is indeed biasing participant judgment (the relative underestimation of angle judgment for the 60° FOV), it is working against a bias encouraging the general overestimation of relative angle judgments.

A likely candidate for this bias lies in how relative angle judgments were collected. In Alexander et al. (2005), participants reproduced the location of highlighted terrain points from an SVS display on a 180° outside world display. For this procedure, the virtual space effect would likely have produced the observed behavior (underestimation of angles). Because the outside world display was conformal (GFOV = EFOV), and the nonconformal SVS display had GFOVs larger than the EFOV, the participants would have interpreted the relative angles of terrain points in the SVS display as being smaller than they actually were in the outside world display. In this experiment, participants made relative angle judgments on an overhead, navigation-like display (an orthogonal projection of 3D space; FIGURE 5). Given that this does not result in the direct GFOV inconsistency seen by Alexander et al. (2005), it is not surprising that different results were obtained.

Hypothesis 5

Participants overestimated angles more for points below the aircraft than for points above it (FIGURE 6). This is consistent with Hypothesis 5 that participants would overestimate relative angle judgments for points below the aircraft compared to points above the aircraft due to the filled distance effect.

Further evidence of the filled distance effect is seen in the Angle × Height interaction for A_e. Here, participants overestimated relative angles the least for points with large angles that were above the aircraft than for the other three levels (FIGURE 6). This is compatible with the filled distance effect because points with large angles above the aircraft would contain less terrain data (more sky) in the screen space used to represent them than there would have been for the other three levels.

Although not hypothesized in this experiment, participants' tendency to underestimate relative distances for points below the aircraft and overestimate them for points above the aircraft in D_e's Angle × Height interaction (FIGURE 7) may also be due to the filled distance effect. Points above the aircraft have more on-screen space devoted to displaying the terrain leading up to them (where terrain is displayed from the bottom of the display, past the horizon line, and up to the terrain point) than for points below the aircraft (where terrain is displayed from the bottom of the display up to the terrain point). Thus, the observed behavior is consistent with the filled distance effect given that SVS displays convey more terrain data for points above the aircraft than those below.

Hypothesis 6

The small negative correlation observed between P_e and τ_e (r = –.18) contradicts Hypothesis 6 that τ_e would be directly proportional to P_e. However, a correlation analysis between D_e and τ_e revealed a much larger positive correlation ($r = .77$, $p < .01$). This would suggest that participants' abeam time judgments were more significantly biased by their relative distance judgments than the abeam point position their relative angle and distance judgments implied. This is further supported by the similarities seen between levels of the distance main effect for D_e (FIGURE 7) and τ_e (FIGURE 9), where participants overestimated abeam time judgments and relative distance judgments for near distances and underestimated them for far distances. There were also similarities between the interaction effects for both D_e and τe. For both the Angle × Height and Angle × GFOV interactions, the ordinal rankings of each of the factor levels in terms of mean directional error are identical (FIGURE 7 and FIGURE 9).

A potential explanation for this bias is that it was cognitively easier for participants to use the relative distance of the terrain point in the derivation of abeam time than to use the relative position of the abeam point.

Compound Biases

The interaction effects illustrate how biasing factors may be compounded. In the H_e main effects (FIGURE 8), participants underestimated relative heights least when points had large angles, near distances, or were presented on 30° GFOV displays. They underestimated them more when points had small angles, far distances, or were presented on 60° GFOV displays. For the Angle × Distance interaction, participants overestimated relative heights (underestimated them the least) for points with large angles and near distance. For the Angle × GFOV interaction, participants underestimated heights the least for points with large angles on a 30° GFOV. For the Distance × GFOV interaction, participants underestimated heights most for points with far distances on a 60° GFOV.

Other Observed Biases

It is not clear why, for A_e's Angle × GFOV interaction, participants underestimated relative angles least for points with large angles on 60° GFOV displays (FIGURE 6). Future work may investigate the sources of this bias.

CONCLUSIONS

The spatial awareness measures introduced by this study have proven useful in identifying spatial biases in SVS displays. By evaluating spatial awareness through the use of four spatial judgments (relative angle, distance, height, and abeam time), the results obtained for these measures have shown that SVS displays do distort spatial awareness due to between-map scale differences in GFOV, within-map differences in orientation, within-map differences in distance, and the virtual space effect. Further, because these factors distort perception of relative distance, they appear to distort participants' ability to make time-to-contact judgments. SVS also appear to be prone to perceptual distortions caused by the filled distance effect.

Of the observed biases, most were very small, making them of relatively little consequence in a design or training context. For example, there was only a difference of 1.37° between average A_e for the two GFOVs. However, several biases deserve some additional attention. The largest biases were associated with within-map differences in distance, with participants overestimating point distances an average of 0.46 nm for near distances (FIGURE 7), underestimating point distances an average of 0.46 nm for far distances (FIGURE 7), and underestimating point heights an average of 164.06 ft for far points.

Although these underestimations are large, it is not clear how dangerous they are given that underestimation may lead pilots to be proactive with respect to avoidance. However, it is clear that overestimation is potentially hazardous as it constitutes an underestimation of the terrain's threat. Further, overestimation of close terrain's relative position is more dangerous than comparable overestimation of terrain that is farther away given that the close terrain constitutes a more immediate threat. Because of this, participants' significant overestimation of the relative distance for points with near distances is potentially unsafe. This is illustrated even further given the significant correlation found between relative distance judgments and abeam time judgments, where participants overestimated abeam times by an average of 11.43 sec for near distances (FIGURE 9).

There are several different ways to compensate for this bias, or any of the other biases found in this experiment. First, pilot training for certification with SVS displays could educate pilots about the spatial biases and help train them to perceive spatial quantities on SVS displays more accurately. Second, SVS designers might investigate purposely distorting the representation of 3D space in the displays to compensate for pilot biases. For example, designers could compress the relative distance of terrain close to the aircraft to compensate for pilot overestimation of its relative distances. However, such a procedure would need to be undertaken cautiously as distortions could beget or contribute to other spatial biases. Last, pilots could be given additional instrumentation (either in the SVS displays themselves or on additional displays) to help them make accurate spatial judgments. For example, work by Borst, Suijkerbuijk, Mulder, and Van Paassen (2006) has investigated the use of additional symbology (based on the options afforded by the aircraft's flight envelope) in vertical situation displays and SVS displays to enhance vertical spatial awareness of terrain.

However, before any of these options can be undertaken, a mathematical model of how a given bias (or biases) impacts spatial awareness is necessary. Such an effort would require that, for multiple subjects, multiple spatial judgments be collected across the range of spatial geometries (relative angle, distance, height, etc.) to which the bias was sensitive. These data could then be used to derive a predictive statistical model (for an example of such an effort, see McGreevy & Ellis, 1986).

Although the use of the new spatial awareness measures generally served their purpose, a potential limitation was elucidated by the discrepancies seen between this and the Alexander et al. (2005) study. This discrepancy illustrates how experimentally observed spatial biases may be impacted by the judgment collection procedure. Although more experimentation is necessary, the community may need to establish a standard concerning what frame of reference should be used for spatial awareness in SVS to resolve this issue.

Finally, because they have proven successful for this study, the new spatial awareness measures may prove useful in future SVS evaluation (different display sizes, mathematical modeling of spatial biases, etc.) and other display technologies for which accurate operator spatial awareness is critical. However, there are limited generalizations that can be drawn from this study given the artificiality of its procedure: Scenarios were short and independent of each other, the in-flight segments were noninteractive, and the terrain point was indicated using an unrealistic object. Thus, this procedure could potentially be improved by incorporating the spatial awareness judgments into more realistic flight scenarios and using more realistic terrain point indicators such as runways and towers.

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