

SPATIAL AWARENESS BIASES IN SYNTHETIC VISION SYSTEMS DISPLAYS

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Synthetic Vision Systems (SVS) create a synthetic clear-day view of the terrain in front of ownship to prevent controlled flight into terrain. To investigate how spatial biases manifest themselves in SVS displays, an experiment was conducted. Eighteen pilots made spatial judgments (relative angle, distance, height, and abeam time) regarding the location of terrain points displayed in 112 5-second videos of a SVS head down display. Judgment errors revealed expected and unexpected spatial biases. Knowledge of these biases will allow SVS engineers to compensate for them and to improve spatial awareness in future SVS designs.

Introduction

Controlled Flight Into Terrain (CFIT), where a fully functional aircraft is inadvertently flown into the ground, water, or other terrain obstacle, has caused more than 25% of commercial aviation accidents since 1987 (Boeing, 2006). CFIT accidents are characterized by a loss of awareness in low level flight and low visibility conditions (FSF, 1999). Synthetic Vision Systems (SVS) combat this problem. By using onboard terrain and obstacle databases and Global Positioning System data, SVS displays create a synthetic, clear-day view of the world surrounding ownship regardless of visibility.

Spatial Awareness and Spatial Biases

Spatial awareness is defined as the extent to which a pilot notices objects in the surrounding environment (Level 1), his understanding of their relative location to ownship (Level 2), and his understanding of their relative location to ownship in the future (Level 3) (Wickens, 2002). This is relevant to SVS since it encompasses a pilot's knowledge about the relative position of terrain. Because SVS use 2D perspective displays (a 3d space projected on a 2d display), spatial awareness can be impacted by spatial biases commonly associated with this type of display.

Resolution. People tend to underestimate the distance between two objects as the amount of screen space used to represent that distance (the resolution) decreases (Wickens, 2002).

Between-map Scale Differences in Field of View. Field of View (FOV) refers to the angular boundaries of the volume of space represented on a perspective display. Increasing a constantly sized display's FOV reduces the resolution of the space represented in it, decreasing the magnitude of perceived distances (Wickens, 2002).

Within-Map Differences in Orientation. In 2D perspective displays, the amount of resolution used to

represent a distance decreases as the distance aligns with observer's line of sight. Thus distances along the line of sight are perceived as being smaller than distances perpendicular to it (Wickens, 2002).

Within-Map Differences in Distances. In 2D perspective displays, the amount of resolution used to represent a distance decreases as distance from the observer increases. This can result in farther distances being underestimated as compared with closer distances (Wickens, 2002).

Time. Because a time to contact judgment is a derived quantity (distance/velocity), people tend to bias these judgments in favor of distance estimates because they are cognitively easier to estimate (Wickens, 2002).

The Virtual Space Effect. The virtual space effect occurs when there is a discrepancy between the angle formed between the edges of the display and the viewer's eyes (the viewing angle) and the FOV represented in the display (McGreevy & Ellis, 1986). When the viewing angle is smaller than the display's FOV, people will interpret objects as being closer together than they actually are. When the viewing angle is larger than the display's FOV, people will interpret objects as being further away than they actually are.

Measuring Spatial Awareness

In SVS and related research, performance measures include cross track error (Schnell & Lemos, 2002), the number of correct identifications made when matching video of actual terrain to SVS displays (Schnell & Lemos, 2002), ordinal distance judgments (Yeh, 1992), the reproduction of the location of terrain points on a SVS display on out the window displays (Alexander et al., 2003), and azimuth and elevation angle judgments of the relative position of two objects over synthetic terrain (McGreevy & Ellis, 1986). Subjective awareness measures have also been

used: Situation Awareness Rating Technique (SART) (Hughes, & Takallu, 2002), Situation Awareness – Subjective Workload Dominance (SA-SWORD) (Hughes & Takallu, 2003), and terrain awareness (Glaab & Hughes, 2003).

None of the measures directly probed pilot knowledge of all three levels of spatial awareness. Thus they do not allow researchers to evaluate how spatial biases manifest themselves in SVS displays.

Objectives

The results herein were part of a larger study designed to evaluate new judgment based measures of spatial awareness (see Bolton, Bass, & Comstock, 2007; Bolton & Bass, 2007a; 2007b). Participants provided relative angle, distance, height, and abeam time judgments with respect to the location of a point shown on SVS terrain during short non-interactive simulations. Identifying the terrain point probed Level 1 spatial awareness. The 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).

Because these new measures probe pilot comprehension of four different spatial dimensions (angle, distance, height, and time), they support the experimental investigation of the spatial biases Wickens (2002) predicted. This paper investigates how these different spatial biases impact spatial awareness for SVS displays based on the relative location of terrain and the display’s FOV.

Methods

Participants

Eighteen general aviation pilots participated in the study. All participants had less than 400 hours of flight experience (*Mdn* = 140, range = [65, 300]). They were familiar with the out the window view from a cockpit but not with SVS displays.

Apparatus

Experiments were run in a windowless constantly lighted laboratory. Workstations displayed each simulation and collected participant judgments. SVS displays were 9.25 in. by 8 in. and used the symbology depicted in Figure 1. 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 flight at 127 knots. They were displayed as 5 second, 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).

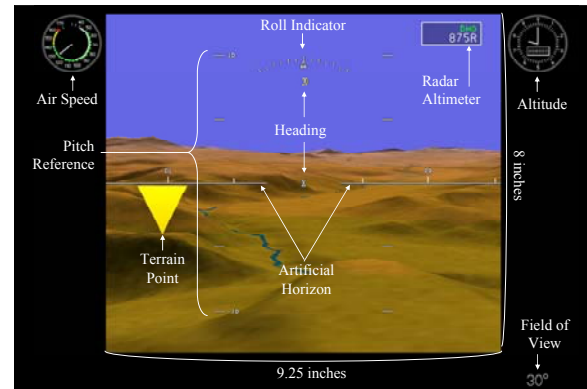


Figure 1. The SVS display used in the experiment.

Independent Variables

Within Subject Variables. There were five within subject variables. These included texture, FOV, and three scenario geometry variables: the relative distance, relative angle, and relative height of the terrain point. Seven textures (Figure 2) and two FOVs (30° and 60°) were used in the SVS displays.

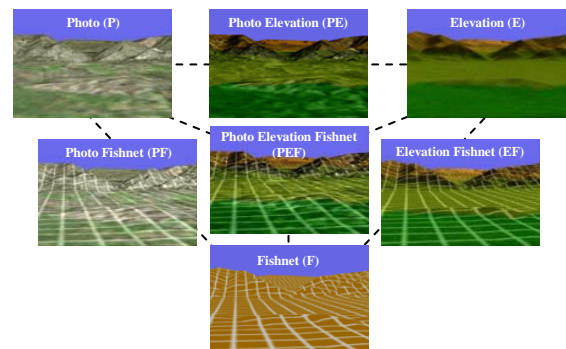


Figure 2. The terrain textures evaluated (P = Photo, E = Elevation, and F = Fishnet).

The location of the terrain point varied based on its relative position at the end of a scenario by changing the three scenario geometry parameters. Each of the variables had two levels (Table 1).

Table 1. Terrain point position Level encoding.

Variable	Range	Distribution	Level
Angle	[0°, 6.5°]	$N(\mu=3.8, \sigma=1.3)$	Small
	[8.5°, 15°]	$N(\mu=11.3, \sigma=1.3)$	Large
Distance	[1 nmi, 3.25 nmi]	$N(\mu=2.3, \sigma=0.4)$	Near
	[3.75 nmi, 6 nmi]	$N(\mu=4.8, \sigma=0.4)$	Far
Height	[-1000 ft, -100 ft]	$U(-1000, -100)$	Below
	[100 ft, 1000 ft]	$U(100, 1000)$	Above

Between Subject Variables. There were two between subject variables: FOV order and texture order. A participant either saw all of the 30° FOV trials first or all 60° FOV trials first. Thus, FOV order had two levels: 30° FOV first or 60° FOV first.

Textures used to derive other textures always appeared before their derivatives. 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}.

Dependent Variables

Directional error dependent variables were calculated from the four judgment values: relative angle (°), relative distance (nmi), relative height (ft), and abeam time (s). Each directional error term represented both the direction and magnitude of the error in the judgment value. When a participant overestimated a judgment, the error was positive. When he underestimated a judgment, it was negative.

Hypotheses

Hypothesis 1. Equal relative angle, distance, and height values are represented with less resolution in displays utilizing a 60° FOV than displays utilizing a 30° FOV due to between map scale differences in FOV. This suggests participants will underestimate position judgments for the 60° FOV as compared to the 30° FOV.

Hypothesis 2. 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 in SVS displays, the relative distance of the terrain points with small angles are represented with less resolution than terrain points with large angles. This suggests that participants will make smaller relative distance judgments for small angles than for larger ones.

Hypothesis 3. Because of the within map differences in distance in SVS displays, heights for far points are represented with less resolution than those with near distances. This suggests that height judgments will be underestimated for far distances compared to closer ones.

Hypothesis 4. Because SVS displays exhibit within map differences in distance, distances are represented with less resolution the further they get from the observer. This suggests that relative distance judgments will be underestimated for far distances as compared to near distances.

Hypothesis 5. Alexander et al. (2003) found that participants underestimated the relative angle of terrain points when reproducing their location in out the window displays (attributed to the virtual space effect). A similar bias is expected for the relative angle judgment in this study.

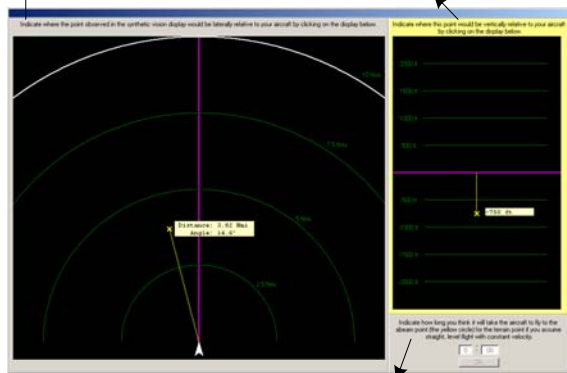
Hypothesis 6. Because abeam time is derived from perceived relative distance and velocity (distance / velocity), and distance is cognitively easier to estimate, participants will tend bias their abeam time judgment in favor of the relative distance judgment.

Procedure

The participants completed consent forms and were briefed about the experiment. Each was randomly assigned to a workstation and experimental condition. Each viewed five second simulations of an SVS heads down display in flight (Figure 1). At the end of the five seconds, the simulation paused for one second, and the screen was cleared. 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 3. For training trials, participants were given feedback relating to the accuracy of their judgments. Participants were asked to work as quickly and accurately as possible.

All participants experienced 112 counterbalanced experimental trials (7 textures × 2 FOVs × 2 Relative Angles × 2 Relative Distances × 2 Relative Heights = 112). For the first texture experienced for each FOV, there were 12 training trials. For the other textures, for each FOV, there were 4 training trials. Thus, each participant saw 72 training trials, resulting in a total of 184 trials.

Indicate where the point observed in the synthetic vision display would be laterally relative to your aircraft by clicking on the display below. Indicate where the point would be vertically relative to your aircraft by clicking on the display below.



Indicate how long you think it will take the aircraft to fly to the above point (the yellow circle) for the terrain point if you assume straight level flight with constant velocity.

Figure 3. The judgment collection interface.

On completion of all of the trials for each texture for each FOV, subjective Demand (where participants assessed how the display configuration placed demand on attentional resources), Awareness, and Clutter (where participants assessed how cluttered each configuration was) ratings were collected using 100 point Likert scales. After all of the trials for a FOV were completed, participants made SA-SWORD pair-wise comparisons between each texture seen with that FOV. After all the trials were complete, participants indicated which FOV provided the best terrain awareness for each texture.

Design and Data Analysis

The experiment employed a repeated measures design with eighteen participants. Three participants were randomly assigned to each of the six combinations of the between subject variables (2 FOV orders \times 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 variables were assessed using a univariate repeated measures analyses of variance with a Type III sum of squares (Brace, Kemp, and Snelgar, 2003). A Pearson's correlation coefficient was used to assess whether participant directional time errors were proportional to directional distance error.

Results

Results for the main effects are reported using $\alpha = 0.05$ for significance and $\alpha = 0.1$ for trends (Table 2).

Table 2. Significance and trends in main effects.

Independent Variable	Directional Error			
	Distance	Angle	Height	Time
Angle			X	
Distance	X	X	X	X
Height	*	X		*
FOV	X	X	X	

X $p < 0.05$. * $p < 0.10$.

Directional Distance Error

Participants, on average, did not overestimate or underestimate relative distances. However, participants underestimated them when points were far and overestimated them when points were near ($F(1,12) = 95.44, p < 0.01$); they tended to underestimate them when points were below the aircraft and overestimate them when points were above the aircraft ($F(1,12) = 3.79, p = 0.08$); and they underestimated them with the 30° FOV and overestimated them with a 60° FOV ($F(1,12) = 7.85, p = 0.02$) (Figure 4).

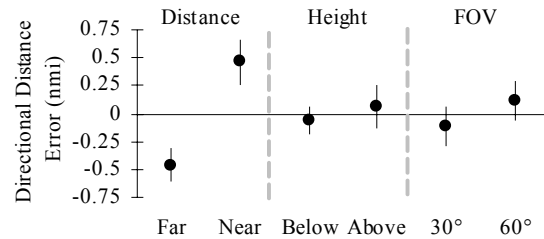


Figure 4. 95% confidence interval plots for directional distance error.

Directional Angle Error

Participants overestimated relative angle judgments ($M = 2.53^\circ, t = 21.73, p < 0.01$). There were also significant differences between individual factor levels: participants overestimated angles more for points with near distances compared to points with far distances ($F(1,12) = 14, p < 0.01$), for points below the aircraft compared to points above the aircraft ($F(1,12) = 16.1, p < 0.01$), and displays with a 30° FOV compared to displays with a 60° FOV ($F(1,12) = 5.06, p = 0.04$) (Figure 5).

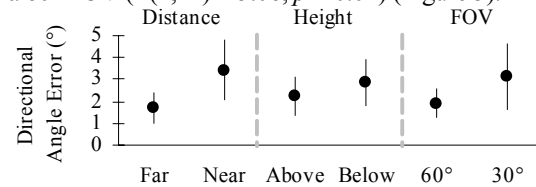


Figure 5. 95% confidence interval plots for directional angle error.

Directional Height Error

Participants underestimated relative height judgments ($M = -81.62$ ft, $t = -11.29$, $p < 0.01$). Participants underestimated their relative height judgment significantly less for points with large angles than for points with small angles ($F(1,12) = 15.89$, $p < 0.01$); points at near distances than for points at far distances ($F(1,12) = 151.34$, $p < 0.01$); and displays with a 30° FOV than for displays with a 60° FOV ($F(1,14) = 5.28$, $p = 0.04$) (Figure 6).

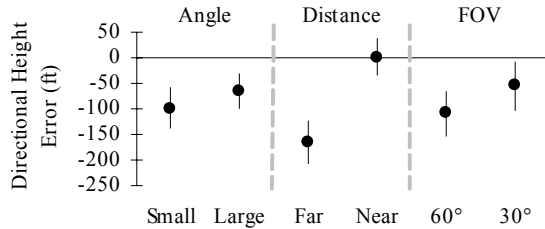


Figure 6. 95% confidence interval plots for directional height error.

Directional Time Error

Participants underestimated relative time judgments ($M = -1.91$ s, $t = -2.61$, $p < 0.01$). Participants underestimated abeam times for points at far distances and overestimated them for points at near distances ($F(1,12) = 61.72$, $p < 0.01$) (Figure 7). They also tended to underestimate abeam times for points below the aircraft but not for points above the aircraft ($F(1,12) = 4.15$, $p = 0.06$).

A Pearson's correlation coefficient for directional distance error and directional time error was significant ($r = 0.77$, $p < 0.01$).

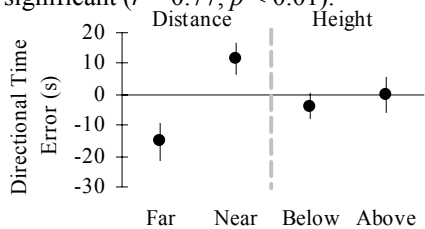


Figure 7. 95% confidence interval plots for directional time error.

Discussion

This study was conducted to determine if known perspective display spatial awareness biasing factors manifest themselves in SVS displays. This study investigated six hypotheses related to these known spatial biases and uncovered additional biases. Four of the hypothesized biases were confirmed, one was contradicted, and one was not present.

Hypothesized Biases

The fact that participants made smaller relative height and angle judgments for the 60° FOV than for the 30° FOV is consistent with Hypothesis 1 (that participants would make smaller spatial judgments for the 60° FOV as compared to the 30° FOV).

There is no evidence to support Hypothesis 2, that participants would make smaller distance judgments for large angles since angle was not significant for directional distance error.

The fact that participants underestimated relative heights more for far distances than for near distances supported Hypothesis 3 (that participants would underestimate height judgments for far distances as compared to near ones).

The tendency of participants to underestimate distances more for far distances than for near distances supported Hypothesis 4 (that participants would underestimate relative distance judgments for far distances as compared to closer ones).

The results indicating that participants overestimated their relative angle judgments contradict Hypothesis 5 (that participants would underestimate relative angle judgments). This indicates that it is not possible to compare the results of the Alexander et al. (2003) out the window results to the procedure herein.

The positive correlation between directional distance and time error reinforces Hypothesis 6.

Other Observed Biases

Participants overestimated relative angles more for near points than for far points. They may have been using the distance of the terrain point from the center of the display to estimate relative angle. In this situation, these distances would be represented with less resolution for far points than near points implying underestimation of relative angle judgments for far points as compared to near points.

Participants overestimated angles more for points above the aircraft than for points below it. A possible explanation for this can be found in the filled distance effect, where participants tend to magnify distance judgments in map displays when more data are encoded in that distance (Wickens 2002). For points above the aircraft, the screen space used to represent its relative angle (above the horizon) will contain less

terrain information (more sky) than the screen space used for a similar point below the aircraft.

Participants overestimated distance for points above the aircraft and underestimated them for points below. 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 theory that SVS displays provide more distance information about points above the aircraft than those below.

Participants tended to underestimate relative heights. It is possible that this is caused by the virtual space effect given both the 30° and 60° FOVs are larger than unity and thus make objects on the screen appear closer together than they would in a unity display. This is also supported by the tendency of participants to underestimate relative heights more with the 60° FOV than the 30° FOV.

Participants tended to underestimate heights more for small angles than for large angles. A possible explanation is that instead of using the relative position of the terrain point from the horizon line for estimating relative height, participants were deriving relative heights from the relative distance of the terrain point from the center of the display. If this were true, participants would be expected to magnify their relative height judgments for points with large angles because the screen distance between the center of the display and terrain point would be larger than for small angles. However, before this bias can be confirmed, further experiments should be conducted which utilize finer angle increments in the experimental design. Such an experiment would allow the bias to be better characterized.

Conclusions

The spatial awareness measures introduced by this study have proven useful in the assessment of 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 have shown how biases related to resolution, between map differences in FOV, within map differences in orientation, within map differences in distance, derived time quantities, the virtual space effect, and the filled distance effect distort pilot spatial awareness in SVS. Thus, the results of this study have the potential to influence SVS design by

documenting biases designers may wish to compensate for.

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 non-interactive, and the terrain point was indicated using an unrealistic object. Thus, the results should be validated by incorporating the spatial awareness judgments into more realistic flight scenarios and using more realistic terrain point indicators such as runways and towers. In addition, the new spatial awareness measures may prove useful in the evaluation of other SVS configurations (display sizes, FOVs, etc) and other displays technologies for which accurate operator spatial awareness is critical.

References

- Alexander, A. L., Wickens, C., & Hardy, T. J. (2003). Examining the effects of guidance symbology, display size, and field of view on flight performance and situation awareness. *Proceedings of the Human Factors and Ergonomics Society 47th Annual Meeting*, Denver, CO.
- Boeing Commercial Airplanes. (2006). *Statistical summary of commercial jet airplane accidents: World wide operations 1959 – 2005*. Retrieved September 9, 2006 from <http://www.boeing.com/news/techissues/pdf/statsum.pdf>
- Bolton, M. L. & Bass, E. J., & Comstock, J. R. (2006). A toolset to support the development of spatial and temporal judgment experiments for synthetic vision systems. *2006 IEEE Systems and Information Engineering Design Symposium*. April 28, 2006, Charlottesville, VA, 58-63.
- Bolton, M. L. & Bass, E. J., & Comstock, J. R. (2007). Spatial awareness in Synthetic Vision Systems: using relative position and temporal judgments to assess the effects of texture and field of view. Manuscript submitted for publication.
- Bolton, M. L. & Bass, E. J. (2007a). Comparing judgment and subjective based measures of spatial awareness. Manuscript submitted for publication.
- Bolton, M. L., Bass, E. J. (2007b). Using relative position and temporal judgments to identify biases in spatial awareness for Synthetic Vision Systems. Manuscript submitted for publication.
- Brace, N., Kemp, R., & Snelgar, R. (2003). *SPSS for psychologists: A guide to data analysis using SPSS for Windows* (2nd ed.). Mahwah, NJ: Lawrence Erlbaum Associates, Inc.
- Flight Safety Foundation. (1999). Killers in aviation: FSF task force presents facts about approach-and-landing and controlled-flight-into-terrain accidents.

- Flight Safety Digest*, 17(11-12), 1-256.
- Glaab, L. J., & Hughes, M. F. (2003). Terrain portrayal for head-down displays flight test. *Proceedings of the 22nd Digital Avionics Systems Conference*. Indianapolis, Indiana: DASC.
- Hughes, M. F., & Takallu, M. A. (2002). Terrain portrayal for head-down displays experiment. *Proceedings of the International Advanced Aviation Conference*. Anchorage, Alaska.
- McGreevy, M. W. & Ellis, S. R. (1986). The effect of perspective geometry on judged direction in spatial information instruments. *Human Factors*, 28(4), 439-456.
- Schnell, T. & Lemos, K. (2002). Terrain sampling density and texture requirements for synthetic vision systems. Rockwell Collins Final Report. Cedar Rapids, IA: Rockwell Collins.
- Stevens, J. P. (2002) *Applied multivariate statistics for the social sciences*. Mahwah: Lawrence Erlbaum Associates, Inc.
- Wickens, C. D. (2002). *Spatial awareness biases*. NASA Technical Report ARL-02-6/NASA-02-4.
- Yeh, Y. (1992). Spatial judgments with monoscopic and stereoscopic presentation of perspective displays. *Human Factors*, 34(5), 583-600.

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