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Effects of Seating Location and Stereoscopic Display on Learning Outcomes in an Introductory Physical Geography Class

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ABSTRACT

Recently, the use of stereoscopic three-dimensional (3-D) projection displays has increased in geoscience education. One concern in employing 3-D projection systems in large lecture halls, however, is that the 3-D effect is reported to diminish with increased angle and distance from the stereoscopic display. The goal of this work was to study that effect in a classroom "real-world" lecture environment where such technology would actually be employed. Introductory physical geography concepts were taught to undergraduate students at the University of Kansas through a GeoWall (passive 3-D projection system) display with either static diagrams or interactive globe imagery (Google Earth). Student learning was gauged using both formative (in-class clicker questions) and summative (exam) assessments. We evaluated the spatial structure of students' formative and summative scores for two concepts: Earth–Sun geometries, taught with static images only, and arid landscapes and aeolian processes, taught with Google Earth only. Three significant results were observed: (1) students' ability to accurately observe the 3-D effect was not restricted to the recommended seating angles when using static images, (2) no spatial patterns of improved learning were observed when using static images only; and (3) a significant difference in learning was observed based on seating angles when using Google Earth. Although this study did not compare learning outcomes against a control group, as would be done in a tightly controlled experimental setting, our findings imply that seating angle should be considered in the design of a new classroom equipped with a stereoscopic display or when choosing an existing classroom to retrofit with this technology, particularly, if interactive, globe imagery, such as Google Earth, is used as a primary teaching tool. © *2014 National Association of Geoscience Teachers*. [DOI: 10.5408/12-362.1]

Key words: GeoWall, seating angle, viewing angle, seating distance

INTRODUCTION

Physical geography is concerned with identifying, describing, and understanding Earth surface objects and the processes that shape them. Atmospheric circulatory systems, supercells, plant canopies, soils, streams, stratovolcanoes, alpine glaciers, fault scarps, parabolic dunes, and coastlines are all examples of objects studied in introductory college, physical geography courses (e.g., Arbogast, 2011; Christopherson, 2011; Petersen et al., 2011). These objects take forms that are inherently three-dimensional (3-D), and most are characterized by irregular geometries. The particular shapes of these objects are contingent on the processes responsible for their formation, which act in varying temporal and spatial contexts, making these objects (e.g., landforms) exhibit a certain amount of randomness in form. The apparent randomness of these objects makes them difficult for students new to the subject to generalize and, ultimately, to categorize conceptually. Students usually have little knowledge or intuition about Earth surface forms and processes (Knuepfer and Petersen, 2002), which compounds the problems inherent in their visualization. In addition, conceptualizing objects at or near the Earth's surface requires spatial thinking (Muehlberger and Boyer, 1961; Kali and Orion, 1996)—a skill not typically developed in most formal education systems (Kastens et al., 2009).

In our teaching experience, the best technique for helping students understand the underlying properties that describe and classify these objects is to provide them with numerous examples from various spatial locations. The more realistic those examples are (especially when beginning to introduce a concept and using more idealized diagrams later [e.g., Goldstone and Son, 2005]), the easier it will be for students to recognize the objects in real-world, physical landscapes and to understand the processes that shape them—a primary goal for this class. Stereoscopic displays, such as a GeoWall (http://www.geowall.org), present material to students in true 3-D and, thus, directly reveal the 3-D nature of the objects under consideration (Johnson et al., 2006; Slocum et al., 2007). That is, stereoscopic displays create the 3-D effect by displaying two perspectives of the same object separately to the left eye and the right eye (Anthamatten and Ziegler, 2006). Although the benefits of 3-D presentation systems in the classroom remain ambiguous (e.g., Trindade et al., 2002; Moreno and Mayer, 2004), it is possible that learning outcomes (i.e., gains in learning) in those courses will benefit from the stereoscopic presentation of course material.

Regardless of whether stereoscopic displays enhance learner outcomes in general, a key issue is that the 3-D effect created by stereopsis is sensitive to seating location (e.g.,

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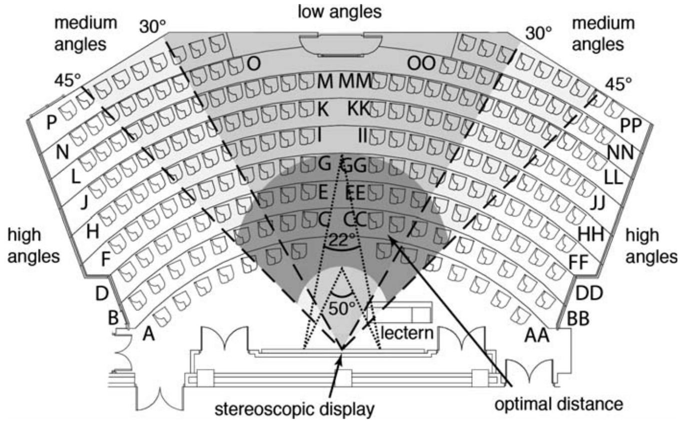


FIGURE 1: Dimensions and arrangement of seats in the classroom used in this study. Letters on either end of the rows refer to blocks of seats (i.e., approximately one-half the seats in most rows) used to randomize student seating assignments. The medium-gray shaded area between the 30° lines refers to recommended seating angles; light-gray shaded areas between 30° and 45° refer to recommended maximum seating angles. The darker band near the center-front row of the classroom refers to the area within the recommended viewing angles (22°–50°), shown as angles between the dotted lines. For scale, the lectern near the stereoscopic display is 0.66 m wide by 2.18 m long. The room is 21.2 m at its widest point and 10.6 m deep.

Shibata et al., 2011). For example, the company THX (San Rafael, CA; currently, the industry standard for high-fidelity, visual reproduction) recommends that audiences be located within 30° left or right of a center reference line drawn from the front to back of the room (Available at: http://www.thx.com). The recommended maximum angle that a viewer should be located with respect to the screen is 45°; the 3-D effect drops off markedly beyond that angle (Fig. 1). Viewing angle controls the distance a student should be located away from the screen to maximize the 3-D effect. THX recommends that viewers be seated with a distance from the screen that would create an angle of 50° between lines drawn from the viewer to each edge of the screen (i.e., the viewing angle) (Fig. 1). Most existing higher-education classrooms, however, were not originally designed to accommodate 3-D stereoscopic displays with these seating angle and distance considerations. Because seating location controls the apparent 3-D effect of such displays, existing classrooms may not be suitable for improving learning outcomes that might otherwise benefit from the 3-D presentation of lecture material.

The goal of our study was to assess the effect of seating location (i.e., seating angle and distance) on learning outcomes in relation to the center of a stereoscopic display in an actual lecture setting. Understanding and quantifying this effect is especially relevant to university instructors and administrators wishing to install stereoscopic displays in large classrooms because this information may dictate which classrooms are chosen for installation of such displays. Additionally, this information may provide recommendations for how classrooms ought to be designed, how many students a classroom can accommodate without losing the 3-D effect, and where those students should sit.

METHODS

Classroom

We installed a permanent, passive polarization-based, dual-projector, interactive 3-D stereoscopic system (GeoWall) in a large classroom at the University of Kansas as part of an ongoing project aimed at evaluating the effectiveness of stereoscopic technology in introductory physical geography courses. GeoWalls and similar systems have been employed since the early 2000s as an effective and immersive visualization tool for research and education (e.g., Steinwand et al., 2003; Anthamatten and Ziegler, 2006; Johnson et al., 2006; Kelly and Riggs, 2006; Rapp et al., 2007; Slocum et al., 2007). The room holds 190 students and is approximately 10.7 m from front to back and 21.2 m at its widest point (Fig. 1).

Because of its width, the room is well suited to evaluate the effect of seating angle on learning outcomes. The distribution of seats within the industry-standard recommended 30° and recommended maximum 45° seating angles is shown as medium gray to light gray shaded areas, respectively, in Fig. 1. There are 64 seats within the 30° seating angles, 56 seats between 30° and 45°, and 70 seats outside the recommended maximum seating angle. Photographs of the screen depicting Stone Mountain, Georgia, directly in front of the screen and at the widest angle from the screen are shown in Fig. 2 for reference.

Viewing angles are defined as the angle made from lines extending from an observer to the edges of the screen (Figs. 1 and A1). Recommended viewing angles range from 22° to 50°, with the former recommendation given by the manufacturer of the screen used in our study (Da-Lite, Warsaw, IN) and the latter offered by THX. The equation relating optimal distance from a stereoscopic projection screen—given the screen width w, viewing angle α, and seating angle θ—can be derived by examining Eq. 1 and Fig. A1.

$$d=\frac{1}{2}w\left[\cos\theta\cot\alpha+\sqrt{(\cos\theta\cot\alpha)^2+1}\right]. \tag{1}$$

The area between the 22° and 50° viewing angles, within the 45° left and right seating angle, is shown as a dark gray band in Fig. 1, mapped using Eq. 1. There are approximately 20 seats in the classroom that fall inside the recommended viewing angles. We informally verified the four seating areas in Fig. 1 (i.e., the low-angle, medium-angle, high-angle, and optimal distances away from the screen) by observing the stereoscopic display from various positions in the classroom.

GeoWall

The GeoWall system consisted of two vertically stacked, 3-D-enabled projectors (EIP-D450, Eiki International Inc., Rancho Santa Margarita, CA) capable of up to 4,500 lumens with XGA (1,024 × 768) resolution, an aspect ratio of 4:3, and an 18-mm digital light processing, DMDX3 imaging system. Each projector was equipped with a 72-mm circular, polarizing filter and mounted with a ceiling 3-D projector stacker (PBM-LP-2A Premier Mounts Stacking System, Caro-Line Holding Co., Fuquay Varina, NC). We used a passive-3-D ready screen (cinema contour, 120-in. diagonal,

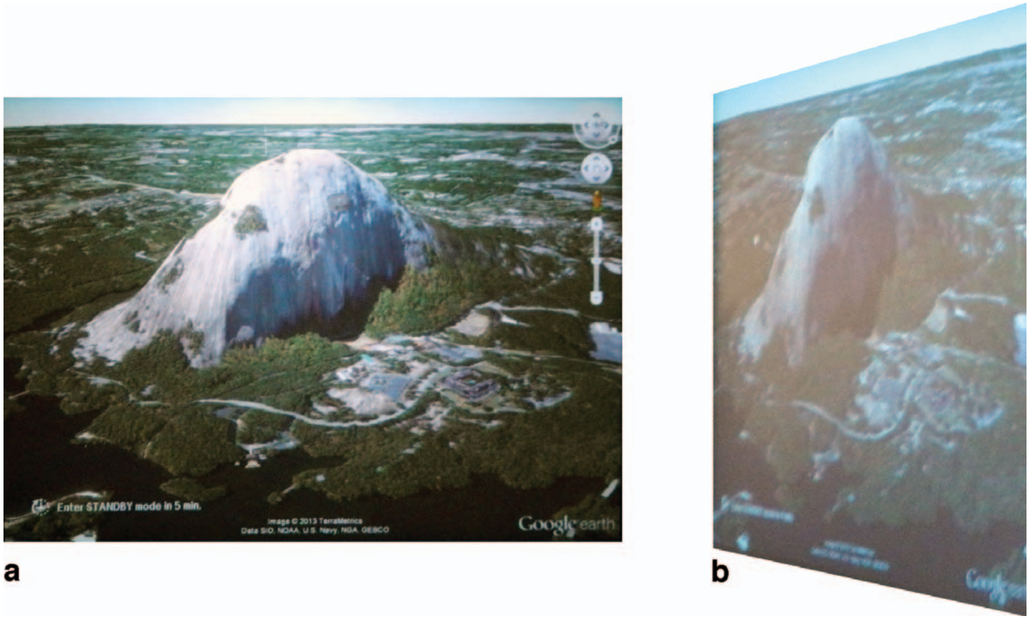


FIGURE 2: Photographs of the screen showing Stone Mountain, Georgia, (a) directly in front of the screen, and (b) at the widest angle from the screen. This image was not used in the study.

3-D virtual grey, Da-Lite, Warsaw, IN) that was 2.43 m wide by 1.83 m tall. In addition, students were provided with circular, polarized glasses to create the 3-D effect.

Stereoscopic Material

Two types of stereoscopic material were used in this study: still 3-D diagrams and interactive globe imagery. Although approximately one-third of the concepts covered in this course used 3-D, we examined seating location effects from material developed for two concepts—(1) Earth–Sun geometry, and (2) arid landscapes and aeolian processes—the first concept using 3-D diagrams, and the second using globe imagery.

Eight static, 3-D diagrams were developed from selected figures in Chapter 3 of *Principles of Physical Geography* (Arbogast, 2011)—a popular introductory textbook. The creation process for each image followed the same general workflow. Google SketchUp (Google, Mountain View, CA) was used to create 3-D models and text; EarthSculptor, a terrain height map builder bundled as a plug-in with iClone Pro (Reallusion, San Jose, CA), was used to create highly detailed topography for certain 3-D models. Because of the incompatibility of the file format outputs from SketchUp and EarthSculptor, we used a 3-D model conversion application—3-DXchange (Reallusion)—to transform .skp and .obj files into a format used by iClone Pro (.vns). iClone Pro places 2-D images and 3-D models into a 3-D workspace or "stage" to create static or animated scenes. The primary reason we adopted that software for our stereo content creation is its ability to convert all scenes into multiple stereo file formats, including the left and right images needed for our stacked, passive projection system. The software also allowed us to control convergence and parallax, the two factors that control stereo vision. In general, all our stereo images and animations were designed to have the center of each 3-D scene appear to rest on the display screen, such that all foreground elements appeared to protrude or "pop out," and all background elements appeared to fall behind the screen. All stereo image backgrounds were shaded with black to match the screen border to avoid visual distractions between the stereo images and the projection screen. A list of selected examples of our 3-D diagram material is given in Table I.

We used interactive globe imagery to show 18 examples of arid landscapes and the aeolian processes within them (concept 2, Table I). Previous work has shown that interactive globes, such as Google Earth, are powerful tools for presenting and visualizing physical geography concepts

TABLE I: Selected topics and several examples within each concept used in this study.

Concept	Topics	No. of Examples
Concept 1: Earth–Sun geometry	Solar radiation and Earth curvature	2
	Axial geometry and subsolar point	2
	Orbital positions of Earth during solstices and equinoxes	4
Concept 2: Arid landscapes and aeolian processes	Barchan, linear, parabolic, and star dunes	11
	Yardangs	3
	Alluvial fans	2
	Horst and grabens	2

(Patterson, 2007; Bailey, 2010). We used Google Earth to present "real-world" examples of physical geography concepts in the classroom, which, compared with the 3-D diagrams created for concept 1, appeared to more consistently hold students' attention. To allow Google Earth to be displayed in stereo 3-D, we used TriDef Visualizer software (Dynamic Digital Depth, Los Angeles, CA).

Student Seating

The study was conducted during the fall semester of 2011 in a single 186-student section of GEOG 104 "Principles of Physical Geography" at the University of Kansas. Students were assigned blocks of seats in the classroom at random for each lecture so that, for every class meeting time, each student had an equal chance of viewing the material from an optimal location. The block arrangement is shown in Fig. 1. Single-letter codes correspond to blocks on the left side of the classroom; double-letter codes correspond to the right side. Except for the first and last row of seats, the rows on each side were divided in half to make a block of seats (Fig. 1). For example, the second row from the font on the left side of the classroom was divided into an outside block of seats (B) and an inside block of seats (C). Block codes were printed directly on the seats and posted on the walls at the end of each row.

We used the random-number generator in Excel (Microsoft, Redmond, WA) to ensure students were assigned a block at random. Block assignments were posted on Blackboard and e-mailed to each student before lecture. In addition, block assignments were posted inside the classroom 15 min before the start of lecture. Students were allowed to sit anywhere within their assigned block. Seats were labeled with a unique code (1–190), and students used a clicker system (i>clicker2, Macmillan New Ventures, New York, NY) at the beginning of class to register their attendance and provide their seat number. Student lecture attendance for concepts 1 and 2 was 137 (73.7%) and 125 (67.2%), respectively. In addition, each student was given a pair of stereo glasses at the beginning of lecture and was encouraged to wear them when any 3-D material was presented.

Assessment

In the first week of lecture, we evaluated student in-class ability for stereoscopy (i.e., the ability to perceive the depth in an image created from stereo pairs). Because seating location may affect student ability to see in 3-D, we conducted a second stereopsis exam, a few weeks into the semester, in which the students were assigned different seats. The stereopsis exam consisted of 12 slides each with four white boxes, and one of the boxes was designed to appear to either protrude or recess into the screen if the student could see in stereo. Students were asked to select the square that appeared to be different from the others. The stereopsis effect was isolated by removing any other visual 3-D cue and by ensuring that each box had the same appearance (all had a slight offset). Thus, without the polarizing glasses, all boxes on the screen looked similar. In addition, we asked a final question on the exam, "Did you fail to see any of the squares differently on all of the past 12 images?" Answers to this and the preceding 12 questions were recorded in class using a clicker system.

Within the first week of lecture, students were also required to take an online, multiple-choice, preclass quiz covering all concepts in the course, thus establishing a baseline for learning outcomes. The questions for that quiz were taken largely from previous semesters' exams. Throughout the semester, we asked students a series of multiple-choice questions scattered throughout each lecture on material that had been covered during that class and recorded their answers via the clicker system (approximately 10 clicker questions per lecture). Finally, we recorded student answers to multiple-choice exam questions. The assessment of learning outcomes using those questions was divided into two types: formative assessment (clicker minus preclass scores) and summative assessment (exam minus preclass scores). Preclass scores were not used as a covariate in this study because we defined learning outcome a priori as an intended gain in knowledge and, thus, relative to a baseline (i.e., preclass quiz scores).

Visualization and Statistics

Spatial distributions of the stereopsis-exam results and learning outcomes (formative and summative) were visualized using proportional circle maps created with the sp package (Pebesma and Bivand, 2005; Bivand et al., 2008) in R version 2.14.2 (R Development Core Team, 2012). Spatial independence and anisotropy in learning outcomes were examined with directional semivariograms for each side of the classroom, following Nielsen and Wendroth (2003), using the gstat package at 0°, 45°, 90°, and 135° clockwise, measured from a reference line drawn down the center of the classroom. The semivariogram is calculated from the following equation:

$$\gamma(h)=\frac{1}{2N(h)}\sum_{i=1}^{N(h)}[A_i(x_i)-A_i(x_i+h)]^2, \qquad (2)$$

where $\gamma(h)$ is the semivariance for a lag distance h between pairs of student scores, N is the number of pairs of student scores separated by h, and A_i is the student score at a location x_i along the directional transect (Nielsen and Wendroth, 2003). We calculated a minimum-detectable absolute-effect size for the study, following Lenth (2012). All other statistical analyses were conducted using the R Base package.

RESULTS AND DISCUSSION

Effects of Seating Location on the Stereopsis Exams

Results for both stereopsis exams are shown as proportional circle maps in Fig. 3. Large circles refer to a high ability to see the 3-D effect; small circles refer to a low ability to see the 3-D effect. Black circles represent students who thought they could not see the 3-D effect in any of the questions of the stereopsis exam. The fraction of students who thought they could not see the 3-D effect was 30 out of 163 (18.4%) and 30 out of 153 (19.6%) for the first and second exams, respectively. The total fraction of students who performed poorly on the stereopsis exams (i.e., correctly answering <50% of the questions) was 38 out of 163 (23.3%) for the first exam and 28 out of 153 (18.3%) for the second exam. Fifteen students failed both test 1 and 2 out of a total of 138 students that took both tests. Roughly one-half of the students who failed the first stereopsis exam also failed the

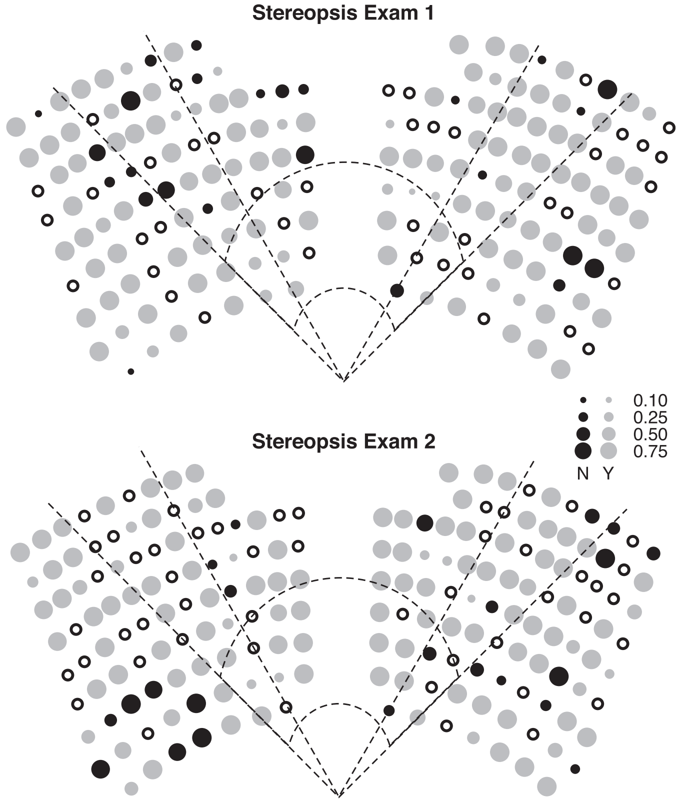


FIGURE 3: Results from the duplicate stereopsis exams, administered at different dates, with students assigned seats at random; scores range from 0 (none correct) to 1 (perfect). Black circles correspond to students who answered that they had not perceived any of the 12 stereopsis questions of the exam in 3-D (N). Gray circles correspond to students who perceived that they had seen at least one of the 12 stereopsis question of the exam in 3-D (Y). Black, hollow circles represent unoccupied seats. Dashed lines refer to the divisions between low, medium, and high seating angles and optimal distances.

second. Stereopsis impairment among the public has been reported with a range from 3% to 30% (Richards, 1970; Ding and Levi, 2011), with other studies estimating stereo-anomolies at 10% or below (e.g., Coutant and Westheimer, 1993; Blake and Sekular, 2005). Interestingly, an average of about 7.9% thought they could not see the 3-D effect and yet were able to answer most of the questions. Conversely, about 9.4% thought they could see the 3-D effect and yet were unable to answer most of the questions.

No obvious spatial patterns are discernible from Fig. 3 either in student scores on the exam or in self-perception of the 3-D effect. To look for possible, subtler patterns of spatially controlled variations, we analyzed the data using semivariograms. When directional semivariograms were plotted for each exam and each side of the classroom, slight anisotropy could be detected in the spatial structure of the right side of the classroom in exam 2 (Fig. 4). That is, the 135° plot appears to have a linear trend in the semivariance for students who are within 2 m of each other. This trend indicates that student ability to see the stereopsis effect is related to the seating angle because the 135° direction cuts across seating angles in the right side of the classroom (Fig. 3). If the data have a spatial structure (i.e., student scores are dependent on seating location), the variance of scores between students seated close together should be smaller than the variance arising from students seated further apart, as evidenced by a trend in the semivariogram.

Because the plots for all but the right 135° in exam 2 do not exhibit an obvious trend, there appears to be no dependence on seating location for those directions. Spatial dependence among the 0° and 135° for the left side of the room or at the 0° and 45° angles for the right side of the room would correspond to a distance effect in stereopsis exam outcomes because those directions cut across viewing angle. Because those directions appear to have had a negligible range, student ability to see the 3-D effect was likely not a function of distance away from the screen in our classroom. However, the slight spatial structure detected across seating angles on the right side of the classroom for exam 2 warrants further investigation.

Stereopsis scores grouped by seating area (i.e., seating angle and optimal distance) are shown in Table II. Low angles correspond to within 30° left or right of the center of the screen, medium angles to within 30° and 45°, and high angles to >45° (Fig. 1). Surprisingly, mean scores for stereopsis exam 1 were 0.70 for students seated in the low-angle area of the classroom, 0.84 for the medium-angle areas, and 0.83 for the high-angle areas. Exam 2 scores were similar to exam 1 for the medium and high angles (0.82 and 0.85, respectively). A larger disparity was observed between the low-angle scores of the two exams (exam 1: 0.70; exam 2: 0.80).

No significant differences ($\alpha = 0.05$) were found when comparing student scores in the three seating angles within each exam by paired *t*-tests. In addition, we compared scores from the optimal distances to scores from the high-angle areas because those scores would likely represent the largest difference in seating location effect; we found no significant differences between those groups. Although the low-angle and optimal-distance areas consistently contained scores that were lower than the medium or high angles—a somewhat surprising finding—there were no significant differences between the four areas in the classroom. Thus, despite the expected differences in seating and viewing angle, students were able to adequately observe the 3-D effect from anywhere in the classroom. Our finding that seating angle did not have a significant effect on visualizing the static 3-D images of the stereopsis exam is analogous to previous work by Cutting (1987) showing that the human visual system is able to tolerate certain amounts of distortions in the projection of objects on those screens observed at high seating angles.

Spatial Patterns of Learner Outcome Types

We plotted proportional circle maps to examine spatial patterns of learner outcome types (Figs. 5 and 6). For reference, the stereopsis score averaged from both exams is plotted for the seating arrangement under which the concepts were taught. Gray circles indicate positive values for formative and summative outcomes; black circles indicate negative values. Positive values for the formative outcomes correspond to better performance on the clicker questions just after the concept was introduced in lecture compared with performance on the preclass quiz questions for the

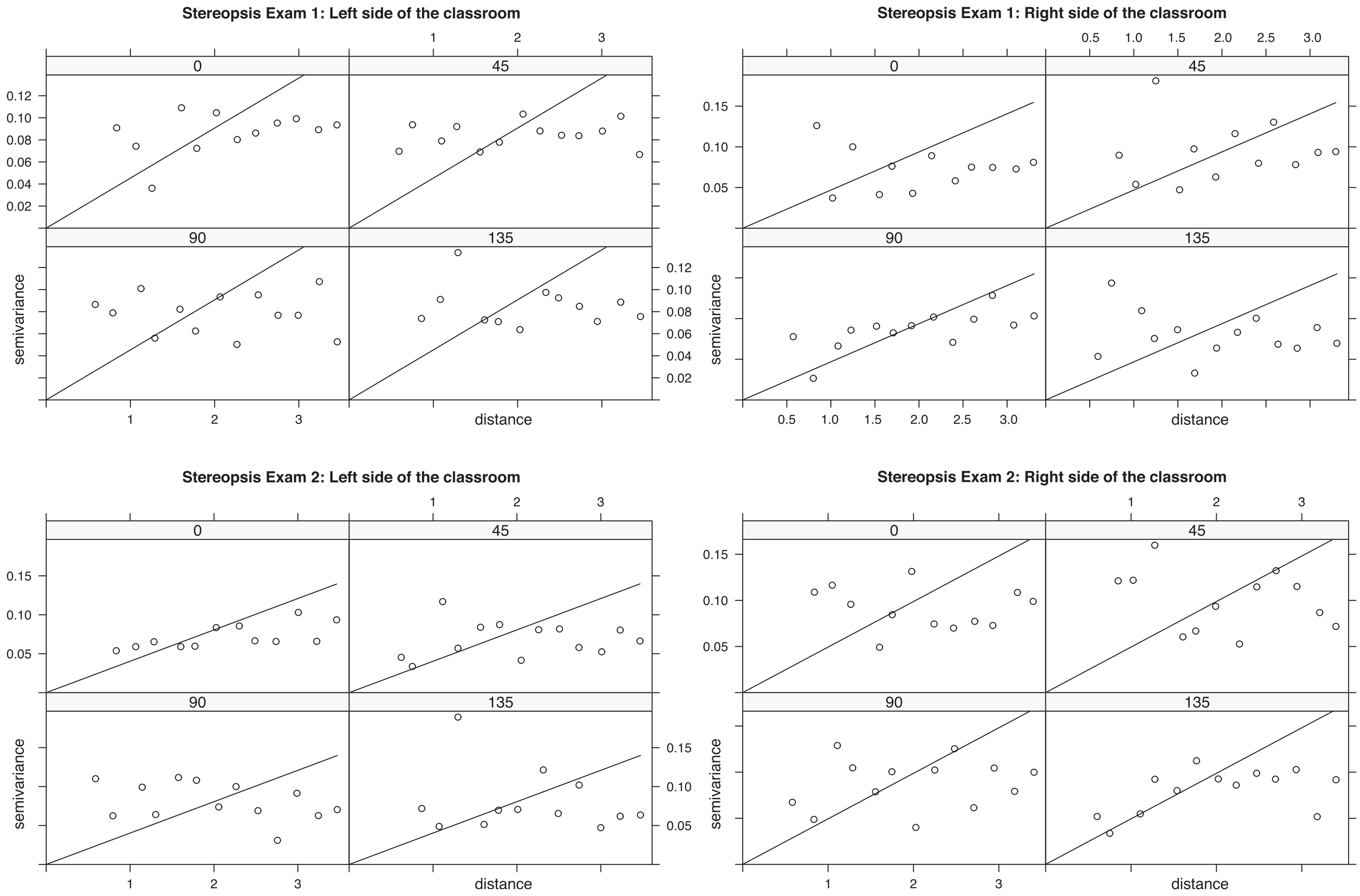


FIGURE 4: Directional semivariograms for each side (left and right) of the classroom for stereopsis exams 1 and 2. The values 0, 45, 90, and 135 correspond to angles in degrees measured from a center reference line drawn from the front to the back of the classroom. The direction is rotated about the center of each side of the classroom. Semivariograms were computed along each of those directions.

TABLE II: Mean scores (0–1) and standard deviations, by seating area, for each stereopsis exam. Seating angles low, medium, and high refer to seats within 30°, between 30° and 45°, and >45° of the center of the stereoscopic display, respectively. Optimal distance refers to the distance calculated from a viewing angle between 22° and 50° and a seating angle within 45°. *N* refers to number students recorded in each seating area. Mean scores for the four seating areas were not significantly different.

Exam	Seating Area	Mean Score	*N*
Stereopsis exam 1	Low angle	0.704 ± 0.342	42
	Medium angle	0.842 ± 0.239	45
	High angle	0.829 ± 0.282	63
	Optimal distance	0.715 ± 0.308	11
Stereopsis exam 2	Low angle	0.804 ± 0.265	42
	Medium angle	0.823 ± 0.299	33
	High angle	0.848 ± 0.255	63
	Optimal distance	0.754 ± 0.342	18

same concepts. Positive summative outcomes result for scores that were higher on the exams taken several weeks after the concepts were introduced compared with the preclass quiz.

For the Earth–Sun geometry unit (concept 1), no clear patterns were discernible in the formative and summative outcomes for either seating or viewing angles (Fig. 5). That is, circle diameters appear to be randomly distributed. Absence of a discernible spatial pattern appears to be confirmed by the lack of a trend in the directional semivariograms for concept 1 (Fig. 7). However, Fig. 6 shows a discernible pattern in the arid landscapes and aeolian processes (concept 2) unit of the class for formative outcomes, in which the scores were higher near the center of the class than they were toward the edges, especially for the left side of the classroom. That pattern does not appear to be present in the summative outcome. The directional semivariograms verified the existence of a slight anisotropy at 90° in both sides of the room corresponding to the across-seating angle direction for the formative outcomes (Fig. 8).

Table III compares mean formative and summative scores for each concept within the four areas of the classroom: low angle, medium angle, high angle, and optimal distance away from the screen (Fig. 1). No significant differences were detected among the paired *t*-

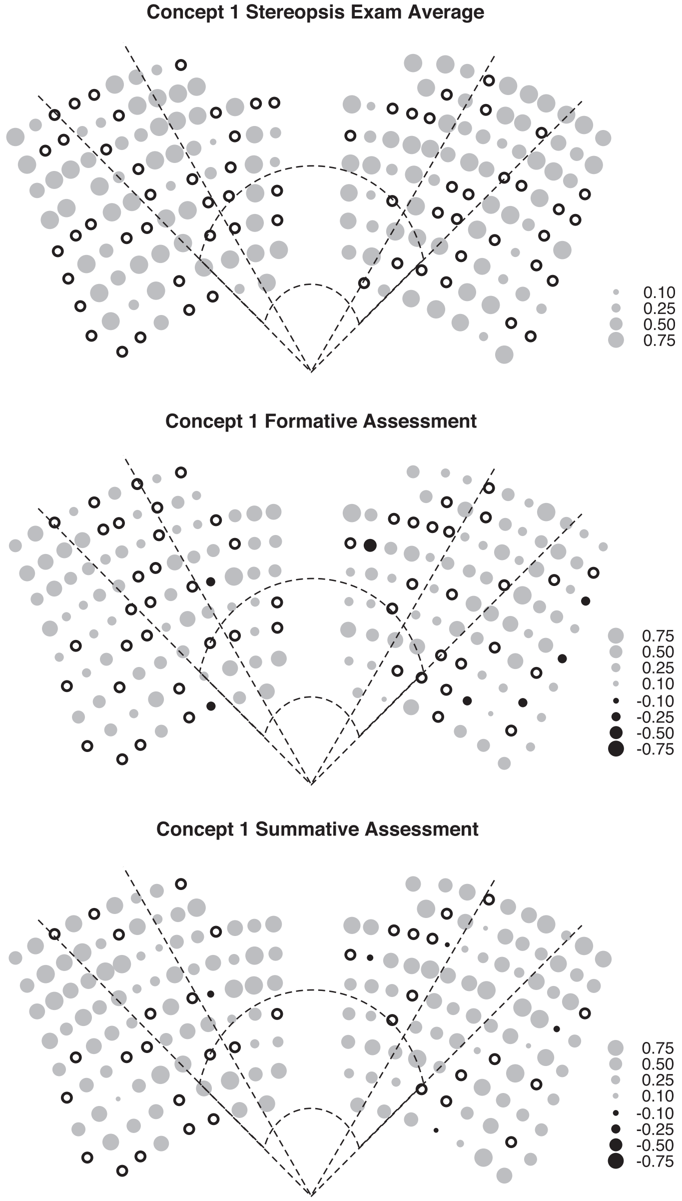


FIGURE 5: Proportional circle maps of average stereopsis exam scores, formative assessment scores (i.e., clicker minus preclass scores), and summative assessment scores (i.e., exam minus preclass scores). These questions were given in the Earth–Sun geometry unit of the class (concept 1). Black, hollow circles represent unoccupied seats. Dashed lines refer to the divisions between low, medium, and high seating angles and optimal distances.

test comparisons for the four classroom areas in formative and summative outcomes for concept 1 supporting the conclusion from the proportional circle map and semivariogram analyses. Formative scores, however, were considerably lower for concept 1 than they were for concept 2.

The spatial pattern observed for concept 2 (Fig. 6) is confirmed in the seating and viewing angle summary of Table III. Formative outcomes were highest for low angles and decreased toward high angles. Significant differences were observed in formative outcomes between low and high angles ($p = 0.042$). No significant differences were observed in summative outcomes for concept 2.

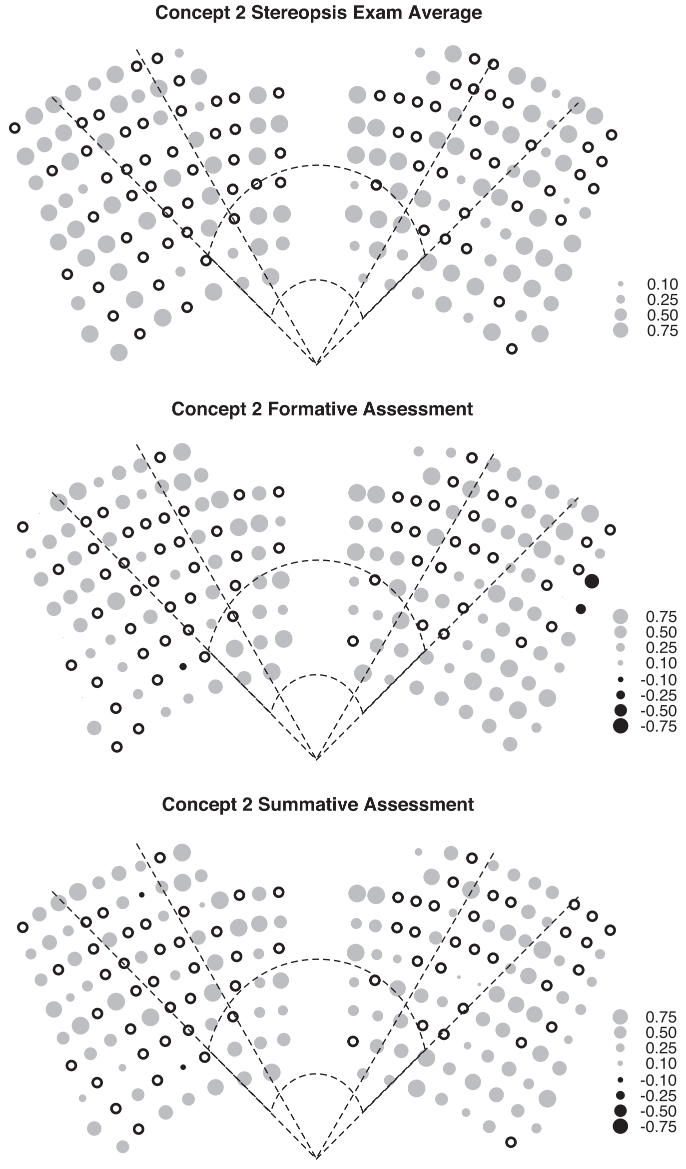
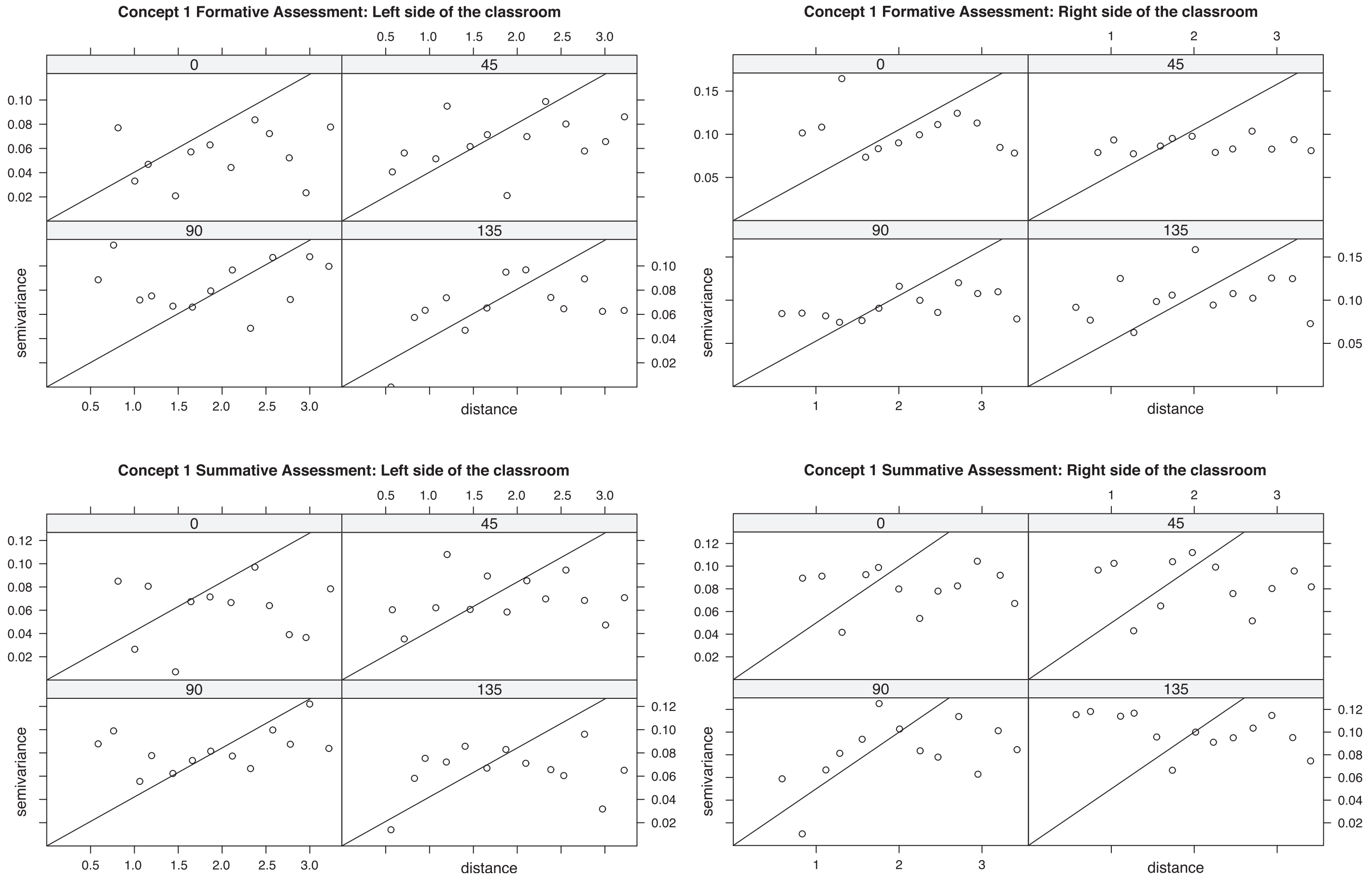


FIGURE 6: Proportional circle maps of average stereopsis exam scores, formative assessment scores (i.e., clicker minus preclass scores), and summative assessment scores (i.e., exam minus preclass scores). These questions were given in the arid landscapes and aeolian processes unit of the class (concept 2). Black, hollow circles represent unoccupied seats. Dashed lines refer to the divisions between low, medium, and high seating angles and optimal distances.

Static Images (Concept 1) Versus Interactive Globe Imagery (Concept 2)

We compared learner outcome types between concepts and found significant differences ($p < 0.001$) among formative outcomes but not among summative outcomes. Student formative assessment scores for concept 2 were significantly higher, when compared with their formative scores, on concept 1 (Table III). That suggests that the spatial



Concept 1 Formative Assessment: Left side of the classroom

Concept 1 Formative Assessment: Right side of the classroom

Concept 1 Summative Assessment: Left side of the classroom

Concept 1 Summative Assessment: Right side of the classroom

FIGURE 7: Directional semivariograms for each side (left and right) of the classroom for the formative and summative assessments of concept 1. The values 0, 45, 90, and 135 correspond to angles in degrees measured from a center reference line drawn from the front to the back of the classroom. The direction is rotated about the center of each side of the classroom. Semivariograms were computed along each of those directions.

patterns observed in the seating angle emerged in concept 2 because of the overall enhanced effect of the 3-D presentation on learning outcomes during lecture for that concept. The improvement of formative outcomes in concept 2, compared with concept 1, could be due to (1) differences between the difficulty level of the lecture material covered, (2) timing effect (i.e., concept 1 was introduced near the beginning of the semester, whereas concept 2 was introduced approximately three-quarters through the semester), or (3) differences between the display techniques used for 3-D presentations for the two concepts. We ruled out the timing effect as an explanation because no trend was observed in lecture clicker scores as the semester progressed. If differences between the lecture material covered explained the difference in formative outcomes between concepts 1 and 2, we would expect to see differences in the summative outcomes as well. Because summative outcomes between the two concepts were not significantly different from each other, we cannot attribute the difference in formative outcomes to differences in difficulty levels between the concepts. Thus, the improvement in formative learning of concept 2 is likely due to the use of the interactive globe software displaying and animating the material. Animated and interactive presentations, in general (i.e., non–3-D), are known to promote learner understanding, especially when used in ways that are consistent with theories of multimedia learning (Mayer and Moreno, 2002). However, the cost of the animation and interactivity can be visual discomfort and fatigue associated with the motor response of the visual system (Shibata et al., 2011), yielding an undesirable spatial pattern in learning outcomes in the classroom.

We queried the students in a midsemester online survey given after both static and interactive presentations were used in lectures to get a feel for student perception of the 3-D material. When asked which topics most benefited from a 3-D view, most students (62%) indicated topics that were presented with the interactive globe imagery were most beneficial, whereas 15% indicated topics with static images. The remainder indicated that either mode of 3-D presentation was beneficial. When asked which topics were least beneficial in 3-D, 5% of the students who responded to that question indicated interactive presentations, as opposed to 60%, who indicated static images; 35% indicated that all the material was beneficial, regardless of 3-D presentation mode. Those statistics appear to confirm the improvement in formative learning of concept 2 was due to that concept being presented with interactive globe imagery.

Implications for Classrooms Using Stereoscopic Displays

We conducted effect-size analysis to examine what minimum difference we could have detected in learning

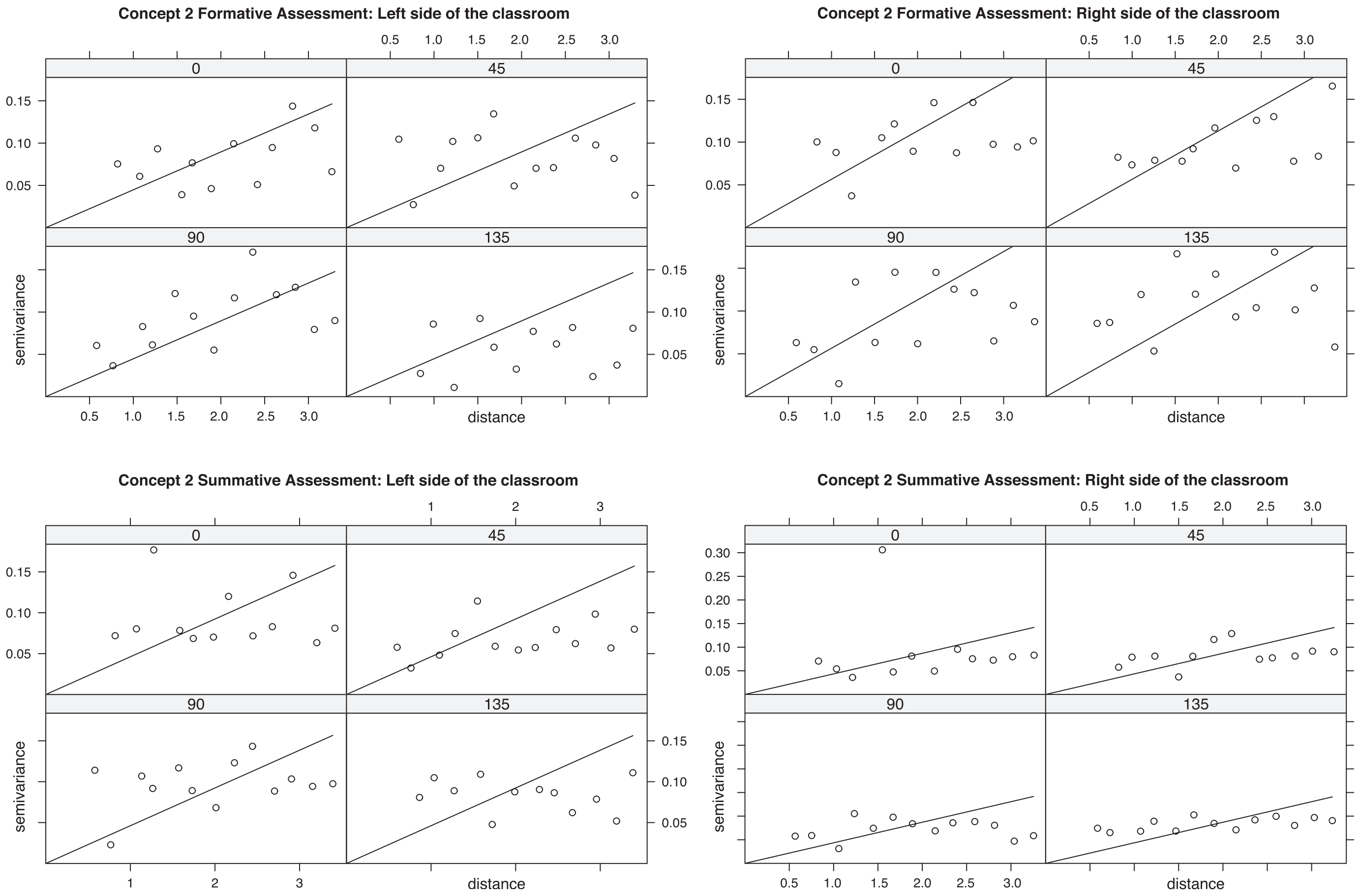


FIGURE 8: Directional semivariograms for each side (left and right) of the classroom for the formative and summative assessments of concept 2. The values 0, 45, 90, and 135 correspond to angles in degrees measured from a center reference line drawn from the front to the back of the classroom. The direction is rotated about the center of each side of the classroom. Semivariograms were computed along each of those directions.

outcomes between the different seating angles used in the class. Given the standard deviation values in Table III, we calculated that our design was able to detect a minimum difference between seating angle areas in the classroom of approximately 9 absolute percentage points, given a power of 0.80 and an α-level of 0.05. That means that seating-angle effects of <9%, if present, were not detected by our paired *t*-tests. The only effects we detected were between high and low seating angles for the formative outcomes in concept 2 with an effect size of 16 percentage points.

Our findings suggest that the effect of seating location is minimal (i.e., less than our minimum detectable difference) when using largely static 3-D images and diagrams to present introductory physical geography–related material (Fig. 9). The effect of the stereoscopic display, however, improved the overall formative learning outcomes by >20

TABLE III: Mean scores (with a range of possible values of between −1 and 1) and standard deviations by seating area (low angle, medium angle, high angle, or optimal distance) for the Earth–Sun geometry unit (concept 1) and the arid landscapes and aeolian processes unit (concept 2) of the class. Optimal distance refers to the distance calculated from a viewing angle between 22° and 50° and a seating angle within 45°. *N* refers to number students recorded in each seating area for the formative and summative assessments.

Concept	Assessment Type	Low Angle	Medium Angle	High Angle	Optimal Distance
Concept 1	Formative	0.355 ± 0.291	0.445 ± 0.261	0.371 ± 0.286	0.385 ± 0.298
	N	43	39	55	17
	Summative	0.570 ± 0.292	0.677 ± 0.248	0.648 ± 0.254	0.604 ± 0.218
	N	47	48	61	19
Concept 2	Formative	0.668 ± 0.283	0.623 ± 0.227	0.506 ± 0.330	0.668 ± 0.264
	N	39	30	56	17
	Summative	0.563 ± 0.270	0.580 ± 0.284	0.570 ± 0.262	0.613 ± 0.226
	N	39	29	56	18

percentage points (i.e., the difference of two letter grades) when using interactive globe imagery, such as Google Earth, compared with static 3-D images. The downside to the result of enhanced learning outcomes because of the interactive software was a detectable effect of seating location, in which average scores between high and low seating angles differed by about 16%, which corresponds to a difference of one and possibly two letter grades on formative assignments between students seated in high versus low seating angles.

Thus, we recommend care in selecting classrooms to be retrofit for a stereoscopic display, especially if—as is increasingly the case—the material to be presented and software to be used requires on-the-fly interaction, such as landscape concepts taught in Google Earth. Seating angles should be kept within the manufacturer-recommended limits of 45°. Viewing-angle requirements, however, are likely to be less important. These factors translate into decreasing enrollment so students are kept within the appropriate seating angles, choosing classrooms to retrofit that have the appropriate widths, building new classrooms that are designed to accommodate seating-angle restrictions imposed by a 3-D system, or using a large enough screen or multiple screens to avoid seating-angle effects.

STUDY LIMITATIONS

We implemented our experimental design in a real-world, semester-long course setting. As such, the study was subject to several limitations including time constraints when presenting the material, unexpected questions and discussion during lecture, and differences in familiarity with the instructor and kinds of questions asked on exams as the semester advanced. All of these issues add to the uncertainty of the results. Perhaps, the greatest limitation with this study is the lack of a control group. We recommend that future work investigating the relationship of learning outcomes to seating locations in the context of a stereoscopic display use a targeted stereoblind population as a control to isolate the effect from stereopsis. Despite these limitations, however, our results show a spatial structure in learning outcomes that disadvantages students outside the recommended seating angles when using interactive globe imagery.

CONCLUSIONS

We conclude that both the effects of stereoscopic displays and seating location on formative learning outcomes were significant and were magnified when interactive, virtual imagery (e.g., Google Earth) was used to present the 3-D material, as opposed to static 3-D images and diagrams. Spatial patterns of learning outcomes were seen in proportional circle maps and detected with semivariograms. We detected a difference of 16% (absolute) in formative outcomes between students seated in high and low seating angle areas—translating to a difference of at least one and possibly two letter grades in formative assessment when using Google Earth to present lecture material. No significant effect of viewing angle (which controls distance from the screen) on learning outcomes was detected in our study. Our findings suggest that seating angle should be considered in either the design of a new classroom to be equipped with a stereoscopic display or when choosing an existing classroom to retrofit with this technology. This is especially true when lecture material is presented using interactive presentation software.

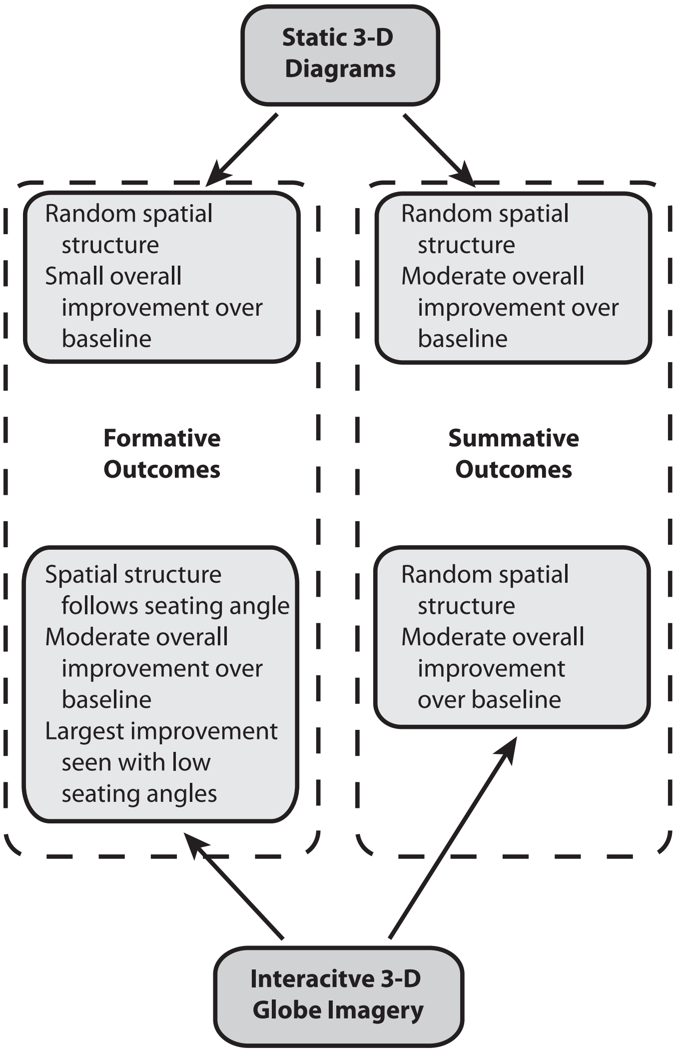


FIGURE 9: Summary of formative and summative outcomes for both static 3-D diagrams and interactive 3-D globe imagery.

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APPENDIX A

We derived the following relationship between distance away from the screen, screen width, viewing angle, and seating angle. See Fig. A1. The line $\overline{AB}$ has a length w, representing the width of the screen. The observer is at point C, and the midpoint of the screen is represented by point D. The lengths of lines $\overline{AC}$ and $\overline{BC}$ are represented by b and a, respectively, and θ and α represent the seating and viewing angles, respectively. The distance from the midpoint of the screen to the observer (i.e., the length of $\overline{DC}$) is represented by d. From the law of cosines, the following relationships can be observed for triangles ΔABC, ΔACD, and ΔBCD:

$$4s^2 = b^2 + a^2 - 2ab\cos\alpha, \tag{A1}$$

$$b^2 = s^2 + d^2 - 2sd\cos(90° + \theta), \tag{A2}$$

$$a^2 = s^2 + d^2 - 2sd\cos(90° - \theta), \tag{A3}$$

where s is $w/2$. Solving these equations simultaneously yields the following:

$$4s^2 = 2s^2 + 2d^2 - 2sd\cos(90° + \theta) - 2sd\cos(90° - \theta) - 2ab\cos\alpha. \tag{A4}$$

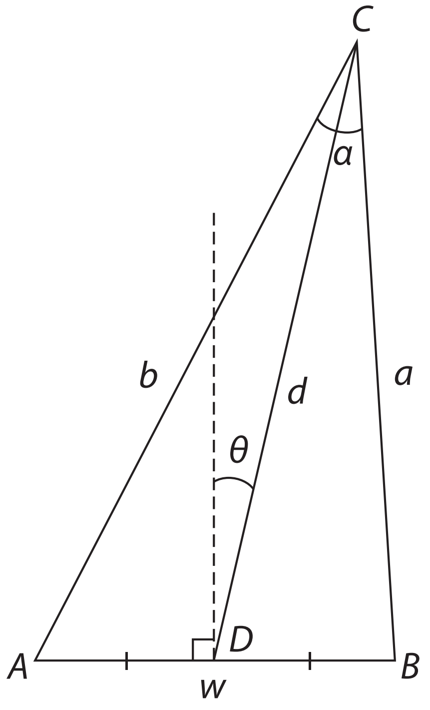

FIGURE A1: The triangles formed between the viewer (represented by point C) and the screen (represented by $\overline{AB}$). Point D is located at the midpoint of the screen, and θ and α represent the seating and viewing angles, respectively.

Expanding the cosine terms and simplifying yields Eq. A5:

$$s^2=d^2-ab\cos\alpha. \tag{A5}$$

Because the area of ΔABC is the sum of the areas of ΔACD and ΔBCD, we use the side-angle-side (SAS) formula to relate the areas of the three triangles as follows:

$$\frac{1}{2}ab\sin\alpha=\frac{1}{2}sd\sin(90°+\theta)+\frac{1}{2}sd\sin(90°-\theta). \tag{A6}$$

Equation A6 can be rearranged to give an expression for *ab*:

$$ab=\frac{2sd\cos\theta}{\sin\alpha}. \tag{A7}$$

Plugging Eq. A7 into the previous equation (A5) and simplifying gives the following:

$$s^2=d^2-2sd\cos\theta\cot\alpha, \tag{A8}$$

which is solved by the quadratic formula to give the following final expression:

$$d=\frac{1}{2}w\left[\cos\theta\cot\alpha+\sqrt{(\cos\theta\cot\alpha)^2+1}\right]. \tag{A9}$$

Thus, given a screen width (w) of 2.43 m, a viewing angle (α) of 22°, and a seating angle (θ) of 45°, the optimal distance between a viewer and the midpoint of the screen would be 4.57 m.