J. Edward Swan II: Promotion Dossier

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May 15, 2010

Dr. Donna S. Reese
Professor and Interim Department Head
Department of Computer Science and Engineering
Box 9637, 300 Butler Hall
Mississippi State, MS 39762-9637

Dear Professor Reese,

Enclosed you will find my application for promotion to the rank of full professor in the Department of Computer Science and Engineering at Mississippi State University. I have found my position at MSU to be both enjoyable and professionally rewarding, and I am looking forward to continuing my academic career at this university.

I have enjoyed the opportunity to teach at MSU; indeed, I voluntarily left a position as a scientist with the Naval Research Laboratory so I could experience academics and teaching. In March 2009 I was extremely gratified to be inducted into the *Bagley College of Engineering Academy of Distinguished Teachers*. The teaching efforts that lead to this award included pioneering (in collaboration with my colleague TJ Jankun-Kelly) a new course, CSE 4/6990 Computer Game Design, which is popular and has now been taught three times. In addition, I updated the curriculum for two courses which, upon my arrival, had not been taught for some years — CSE 8433 Advanced Computer Graphics and CSE 4/6663 Human-Computer Interaction. I have also taught CSE 4/6833 Analysis of Algorithms, which is a core senior class, as well as CSE 2813 Discrete Structures, a core sophomore class. In these classes I have introduced innovations, in particular the lab sequence in Advanced Computer Graphics, the homework grading scheme in Analysis of Algorithms, and the external projects in Human-Computer Interaction. In addition, during Spring 2010 I worked with the Mississippi wireless company Cellular South to provide 8 HTC Hero Android cell phones for use in my Game Design class. This partnership generated significant media interest and resulted in an MSU Press Release, two articles in the Clarion-Ledger, an article in the Delta Business Journal, and a report on WTVA news. I have also constantly striven to improve the quality of instruction for every class; I believe this sustained effort produced the teaching evaluations and recommendation letters that resulted in the Academy of Distinguished Teachers award. In addition to teaching, I have advised 19 undergraduates (including 2 who completed research projects), 11 MS candidates, and 6 PhD candidates. Of these, I have directed or co-directed 2 completed PhD dissertations (one at Virginia Tech), and served on the committee of 2 additional completed dissertations. I have also directed or co-directed 3 completed MS theses, served on the committee of 2 additional MS theses, and advised or served on the committee of 6 additional non-thesis MS degrees.

I have desired a scientific career since I was in high school, and I have found Mississippi State University to be an excellent institution from which to conduct a research program. Broadly described, my research involves conducing human-factors investigations of computer-generated graphics. For the past 8 years, beginning when I was employed by the Naval Research Laboratory, I have been intensively studying how depth perception operates in augmented reality. This work is currently supported by a single-PI NSF

JAMES WORTH BAGLEY COLLEGE OF ENGINEERING MISSISSIPPI STATE UNIVERSITY
J. Edward Swan II, PhD ● Associate Professor ● Computer Science and Engineering
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grant and a NASA grant, and beginning in October will be supported by a second single-PI NSF grant. Previously this work has been funded by NASA, the Office of Naval Research, and my startup resources. I have collaborated with colleagues from NASA Ames Research Center, NVIDIA Corporation, and the University of Rostock. In addition, I have been studying other human-factors aspects of augmented and virtual reality, primarily through collaborations with colleagues at Virginia Tech and the Naval Research Laboratory, but also recently with MSU colleagues at CAVS. Finally, since my arrival at MSU, I have been working in the emerging area of conducting empirical evaluations of visualization techniques. This work is collaborative with several MSU colleagues; it is currently funded by NSF, and has previously been funded by DoD. At MSU these research activities have resulted in 9 journal papers; on 6 of which either myself or one of my advisees is first author. They have also resulted in 13 refereed conference papers; on 7 of which either myself or one of my advisees is first author. Like other fields that have grown out of Computer Science, in my professional community these full-text refereed conference articles are widely read, have a professional impact that is comparable to journal articles, and have very low acceptance rates (the median for my papers is 28%). My research has also resulted in 12 abstracts and short papers, and has generated approximately 1.9 million in research funding. Finally, I have consistently striven for quality in my research and the resulting publications. In Spring 2008 one of my journal papers won the *Bagley College of Engineering Outstanding Research Paper Award*, and in 2006 a conference paper won an *Honorable Mention* award at the IEEE Virtual Reality conference. Four additional papers that I published while at the Naval Research Laboratory received awards as well; two of these awards came from my employer and two from my professional societies (*Best Paper* awards at the IEEE Virtual Reality and IEEE Visualization conferences).

I have enjoyed opportunities to give back to the organizations that make my scientific career possible. My goal has been to be a good citizen of the Computer Science and Engineering Department, the College of Engineering, Mississippi State University, and my larger professional community. To date my departmental service has involved serving on the faculty search committee and numerous other departmental committees. In addition, since 2007 I have served on the Steering Committee of the Institute for Neurocognitive Science and Technology, in the past year I chaired a Five Year Program Review committee for the Department of Psychology, and this year I am beginning a 3-year term as an alternate member of MSU's Human Subjects Institutional Review Board. Professionally, since arriving at MSU I have organized, lead, and taught a series of 7 professional tutorials on conducting human-subject experiments at the IEEE Virtual Reality and IEEE Visualization conferences. These tutorials are popular and influential in my professional community; several times I have been told that they have been the best-attended tutorial offered at the conference, and several times I have been specifically asked to organize the tutorial again for the next year. I have also served on numerous professional program committees, and I have attended numerous review panels organized by the National Science Foundation, the IEEE Virtual Reality conference, the Naval Research Laboratory, and others. Finally, when I worked for the Naval Research Laboratory I held many organizing positions on the IEEE Visualization conference committee; this service cumulated in a 2-year stint as conference program co-chair in 2001 and 2002.

My position in the Department of Computer Science and Engineering at MSU has provided me with an enjoyable and rewarding academic career, and I look forward to continuing my service as a member of the graduate faculty of this department.

Sincerely,

J. Edward Swan II, PhD

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Revised 07/30/10

Mississippi State University
Application for Promotion and/or Tenure

Please check response(s) in both columns	
TENURE:	**PROMOTION:**
______ Mandatory tenure decision	______ Promotion to Associate Professor
__✓__ Not applicable (early promotion or already possess tenure)	__✓__ Promotion to Full Professor
	______ Not applicable (already at associate or full level)

Faculty members eligible for consideration for promotion or tenure must provide the department head or appropriate official with all pertinent available information by **October 1**. The department head or other appropriate official has the responsibility to assist the faculty member in preparing for tenure or promotion review.

Materials to be provided in the applicant's dossier include:

*1. Cover letter from the candidate requesting promotion and/or tenure.
*2. Completed University Promotion and Tenure application form (this cover page and attached pages) with appropriate responses and associated documentation. This must include a summary sheet of teaching evaluations.
*3. Complete up-to-date vita.
*4. Original offer letter and, if necessary, additional letter detailing significant changes.
*5. Letters from external reviewers (to be added by department head). The department head should include a sample letter sent to external reviewers and biographical information about reviewers as appropriate.
6. All materials required by the academic unit's procedural guidelines.
7. All supporting documentation desired by the candidate.

*Only these items will be reviewed routinely above the college level. Items 1-7 must go to dept. head and dept. committee. Deans, college committees, and the Provost require items 1-5 but may also request items 6 and 7. Department heads and deans can use their discretion in sending forward any important information included in items 6 and 7. All department head, dean, and committee recommendations should be included in the package to the Provost.

Note: Applicants may not add information after a departmental decision has been made.

Your offer letter stated that in order to be considered for tenure you must be a citizen of the United States or be eligible for permanent employment in this country.

Are you a U. S. Citizen: __✓__ Yes _____ No (If No, are you a permanent resident: _____ Yes _____ No)

Name of Applicant: _ Dr. John Edward Swan II ______________________________

Present rank: _ Associate Professor ______________ Date of appointment at current rank: _ Aug 2004________

College/School: _ Engineering ____________ Department: __ Computer Science and Engineering__________

Department Head: _Dr. Donna Reese______________________________

Preferred Mailing Address (Include City and Zip Code): _856 South Ridge Road ______________________

______________________Starkville, MS 39759______________________

Initial rank at MSU with date of appointment: _ Associate Professor Aug 2004 ______________________

Tenure track date of appointment: _ Aug 2004______________ Years of transferred service (if applicable): ______

Advanced Degrees with Dates: _ PhD in Computer Science 1997; MS in Computer Science 1992 ______________

Salary Funding (%): E&G: _______ MSU Research Unit: _______ Extension: ______ Other: ______

All other information contained in the attached application is correct, to the best of my knowledge.

Date: ______________________ Signed: ______________________
Faculty Member

I. Current responsibilities:

A. Current instruction

	Course number	Title	Credit hours	Number of Students
1. Undergraduate	CSE 4833	Intro to Analysis of Algorithms	3	17
	CSE 2813	Discrete Structures	3	41
	CSE 4990	Game Design	3	8
2. Graduate	CSE 6833	Intro to Analysis of Algorithms	3	10
	CSE 6990	Game Design	3	4

3: Advises: Undergraduate__7__ Master's/Specialist__3__ Doctoral__2__

B. Current or on-going research/creative/performance activities

- *Depth Perception in Augmented and Virtual Reality*: I have been studying how depth perception operates in augmented and virtual reality for the past 8 years, beginning when I was employed by the Naval Research Laboratory. This work is currently supported by a single-PI 3-year NSF award and a 1-year NASA award, and beginning in November will be supported by a second single-PI 3-year NSF award. It has previously been supported by NASA, the Office of Naval Research, and my startup funds. It involves collaborations with colleagues from NASA Ames Research Center, NVIDIA Corporation, and the University of Rostock. Since my arrival at MSU, this work has resulted in a journal publication, 5 refereed conference publications, 7 other publications, and 2 completed master's theses. I am currently advising 3 PhD students in this area. My laboratory for this work is located at the Institute for Neurocognitive Science and Technology (INST).
- *Human-Factors Aspects of Augmented and Virtual Reality and Simulator Technology*: In addition to depth perception, I have been studying other human-factors aspects of augmented and virtual reality, including text legibility and cell-phone distraction for drivers. This work has involved collaborations with colleagues from Virginia Tech and the Naval Research Laboratory. In addition, I am directing a Cognitive Science PhD student whose dissertation project uses the Driving Simulator at the Center for Advanced Vehicular Systems (CAVS). Since my arrival at MSU, this work has resulted in 3 journal publications, 5 refereed conference publications, and 3 other publications, as well as a completed dissertation (of a Virginia Tech graduate student).
- *Visualization Technique Development and Evaluation*: Since my arrival at MSU, I have worked on the development of new visualization techniques, with a special emphasis on the emerging area of conducting empirical evaluations. This research fills a niche at MSU, and allows me to apply my expertise in both human-computer interaction and visualization in a way that contributes to the long history of excellent visualization research at MSU. This work is collaborative with a number of MSU colleagues. It is currently funded by the National Science Foundation, and has previously been funded by the Department of the Army. In addition, one of my key graduate students in this area brought his own funding from the Naval Research Laboratory. Since my arrival at MSU, this work has resulted in 5 journal publications, 3 refereed conference publications, and 4 other publications, as well as 2 completed dissertations and a completed master's thesis.

C. Current service/administrative assignments

1. Public service and off-campus professional service activities:
   - Served as Session Chair for *IEEE Virtual Reality 2010* (IEEE VR 2010).
   - Served as Posters Fast-Forward Chair for *IEEE Virtual Reality 2010* (IEEE VR 2010).

2. Professional association service, as offices held, etc.:
   - Serving as *Search Committee Member* for the Editor-in-Chief of *IEEE Transactions on Visualization and Computer Graphics*, August–September 2010.
   - Served on Program Committee for *Applied Perception in Graphics and Visualization 2010* (APGV 2010).

- Served on Program Committee for *IEEE Virtual Reality 2010* (IEEE VR 2010).
- Served on Conference Committee for *IEEE Virtual Reality 2010* (IEEE VR 2010), as posters co-chair.
- Served on Program Committee for the *Conference on Visualization and Data Analysis 2010* (VDA 2010).
- Served on *Naval Research Laboratory External Review Panel*, Battlespace Environments and Undersea Warfare Focus Areas (6.1 / 6.2) Marine Geosciences Research Program, Stennis Space Center, MS, USA, July 28–30, 2009.
- Served as *International Symposium on Mixed and Augmented Reality 2009* (ISMAR 2009) Science & Technology Area Chair (attended program committee meeting), Orlando, FL, USA, July 16–17, 2009.
- Served on Program Committee for the *Conference on Visualization and Data Analysis 2009* (VDA 2009).
- Served on Program Committee for *ACM Symposium on Virtual Reality and Software Technology 2009* (VRST 2009).
- Served on Program Committee for the *International Symposium on Visual Computing 2009* (ISVC09).

3. University and departmental committee and administrative accomplishments:
    - *Human Subjects Institutional Review Board* (IRB) (standing), Alternate Member, 2010–2013.
    - Chair of the *Five Year Program Review for the Department of Psychology* (ad-hoc), convened for the Office of the Provost, 2010.
    - *Steering Committee* (standing), Institute for Neurocognitive Science and Technology (INST), 2008–2009.
    - *Courses and Curricula Committee* (standing), Department of Computer Science & Engineering, 2005–2010.
    - *Strategic Planning Committee* (standing), Department of Computer Science & Engineering, 2009–2010.
    - *PhD Qualifying Exam Study Committee* (ad hoc), Department of Computer Science and Engineering, 2008–2010.

D. <u>Other</u>

Musical service to the university:

- *Summer Scholars On Stage 2010*, Division of Academic Outreach and Continuing Education, July 18–24, 2010. Arranged music and played bass guitar in stage band.
- *National Science Foundation Center Dinner* at the Hotel Chester, High Performance Computing Collaboratory, October 29th, 2009. Organized the After 5 Jazz Band, arranged music, sang and played bass guitar.
- *Latin American Night*, Program by the Hispanic Student Association, October 27th, 2009. Worked with Dr. Robert J. Damm (professor of music), assisted with musical arrangements, rehearsed with and taught the music to the students, and played bass guitar on nine songs.
- *Summer Scholars On Stage 2009*, Division of Academic Outreach and Continuing Education, July 19–25, 2009. Arranged music and played bass guitar in stage band.

II. Activities since last promotion (or initial appointment for tenure):

A. Teaching

1. Evidence of quality of instruction (check items submitted):
(The faculty member should provide material describing his/her teaching activities and documentation supporting effectiveness. This material must include a summary statement of student evaluations and may include any of the following, or any other items deemed appropriate: department head evaluation on teaching__✓__, dean evaluation _____, peer evaluations (internal or external) __✓__, self-evaluation of each course taught__✓__, scholarly research/publications related to teaching ______, course syllabi and exams __✓__, teaching grants and awards __✓__, student input in the form of letters, emails, faculty nominations, etc. __✓__, curriculum development and innovation __✓__, developmental activities_____, measures of student success_____, other_____.)

2. Master's students: major professor__8__; minor professor__9__.
Specialist students: major professor_____; minor professor:_____.
Doctoral students: major professor__6__; minor professor__8__.

3. Courses initiated or innovations instituted:

- *Course initiated, Spring 2008: CSE 4990/6990, Computer Game Design*. Before initiating this course, students often expressed their interest in game design to me and my computer graphics colleagues. Computer games are a very important aspect of today's culture — especially youth culture — and furthermore a modern computer game is an extremely complicated and sophisticated engineering project, which also involves significant creative content that is most comparable to motion picture production. I developed the curriculum for this new course in close collaboration with T.J. Jankun-Kelly. To date this course has been popular and has been offered three times, in Spring 2008 (taught by myself), 2009 (taught by Dr. Jankun-Kelly), and 2010 (taught by myself). Dr. Jankun-Kelly and I intend to continue offering this course every Spring semester.

- *Curriculum revised, Fall 2006: CSE 4663/6663, Human-Computer Interaction*. Although this course was already listed, it had not been taught for some years. I developed a completely new curriculum, from the book selection on up, from scratch, with completely up-to-date content. I have now taught this course 3 times, and will offer it for a 4th time Fall 2010.

- *Curriculum revised, Spring 2005: CSE 8433, Advanced Computer Graphics*. Although this course was already listed, it had not been taught for some years, and the previous instructors were no longer at MSU. I developed a completely new course, from the book selection on up, from scratch, with completely up-to-date content. I have now taught this course 3 times.

4. Other (academic advisement may be described here or as service):

Graduate Advising:

Graduated PhD Students (Advisor / Co-Advisor):

- *Chad Steed* (Computer Science & Engineering), co-advisor with TJ Jankun-Kelley, "Development of a Geovisual Analytics Environment using Parallel Coordinates with Applications to Tropical Cyclone Trend Analysis", Mississippi State University, PhD Dissertation, Fall 2008.

- *Joseph L Gabbard* (Computer Science), co-advisor with Deborah Hix (faculty at Virginia Tech), "Usability Engineering of Text Drawing Styles in Augmented Reality User Interfaces", Virginia Polytechnic and State University, PhD Dissertation, Fall 2008.

Graduated PhD Students (Committee Member):

- *Byron Williams* (Computer Science & Engineering), "Change Decision Support: Extraction and Analysis of Late Architecture Changes Using Change Characterization and Software Metrics", Mississippi State University, PhD Dissertation, Spring 2009.

- *Shangshu Cai* (Computer Engineering), "Hyperspectral Image Visualization Using Double and Multiple Layers", Mississippi State University, PhD Dissertation, Fall 2008.

- *Baoquan Chen* (Computer Science), "Image-Based Volume Rendering", State University of New York at Stony Brook, PhD Dissertation, October 1999.

Graduated MS Students (Advisor / Co-Advisor):

- *Gurjot Singh* (Computer Science & Engineering), "Near-Field Depth Perception in See-Through Augmented Reality", MS Thesis, Summer 2010.
- *Alexander Morais* (Computer Science & Engineering), MS Project student, Summer 2009.
- *Dennon McMillian* (Computer Science & Engineering), MS Courses-Only, Fall 2008.
- *Brian Thomas* (Computer Science & Engineering), MS Courses-Only, Summer 2008.
- *Adam Jones* (Computer Science & Engineering), "Egocentric Depth Perception in Optical See-Through Augmented Reality", MS Thesis, Summer 2007.
- *Joe Langley* (Computer Science & Engineering), co-advisor with Susan Bridges, "SCRIBE: A Clustering Approach to Semantic Information Retrieval", MS Thesis, Spring 2006.

Graduated MS Students (Committee Member):

- *Andrew Stamps* (Computer Science & Engineering), MS Courses-Only, Spring 2010.
- *Mouthgalya Ganapathy (Computational Engineering), "Obstacle Array Drag Coefficient Parametric Surface Response Analysis", Fall 2009.*
- *Yagneshwara Lanka* (Computer Science & Engineering), MS Courses-Only, Summer 2009.
- *Joel Martin* (Computer Engineering), "Results of a User Study on 2D Hurricane Visualization", MS Thesis, Summer 2008.
- *David Wilson* (Computer Science & Engineering), "Analyzing Relationships in the Textual Contents of Digital Forensics Evidence", MS Project, Spring 2008.

Current PhD Students (Advisor / Co-Advisor):

- *Teena Garrison* (Cognitive Science), "Applying Driving Simulation to Investigate Law Enforcement Officer Driving Behavior and Performance", PhD student, expected 2010.
- *Adam Jones* (Computer Science & Engineering), "Egocentric Depth Perception in Augmented Reality", PhD student, expected 2011.
- *Gurjot Singh* (Computer Science & Engineering), "Augmented Reality Implementation of X-Ray Vision", PhD student, expected 2011.
- *Sujan Anreddy* (Computer Science & Engineering), topic not yet known, expected 2013.

Current PhD Students (Committee Member):

- *Yagneshwara Lanka* (Computer Science & Engineering), "Tensor Glyph Visualization Techniques", PhD student, expected 2012.
- *Mark Thomas* (Cognitive Science), "Visual Processing and Object Memory", Mississippi State University, PhD student, expected 2011.
- *Chevonne Dancer* (Computer Science & Engineering), "A Platform-Independent Investigative Process Model for Smartphones", expected 2011.
- *David O'Gwynn* (Computer and Information Sciences; University of Alabama at Birmingham), "Semantic Alignment of Surface Meshes", expected 2011.

Current MS Students (Advisor / Co-Advisor):

- *Josh Franck* (Experimental Psychology), "Depth Perception in Augmented and Virtual Reality", MS student, expected 2011.

Undergraduate Research Advising:

- *Lorraine Lin* (Computer Science & Engineering), directed Summer Honors College Undergraduate Research Fellowship "Depth Perception in Augmented Reality", Summer 2009; directed NASA-Funded Research "Development of Haploscope for Near-Field Depth Perception in Augmented Reality", Summer 2010. Directed general lab involvement during the school year as well.
- *Huaiying (Shan Shan) Wang* (Brain & Cognitive Sciences; Massachusetts Institute of Technology (MIT)), directed summer research project "Development of Haploscope for Near-Field Depth Perception in Augmented Reality", Summer 2010.

Other Teaching-Related Activities:

- **Educational Partnership with Cellular South and Resulting Publicity**: During Spring 2010, I worked with the Mississippi wireless company Cellular South to provide 8 HTC Hero Android cell phones for use in my Game Design class. The students developed three games on the Android phones. This partnership generated significant media interest; I was interviewed by Robbie Ward (University Relations) and Susan Lassetter (Bagley College of Engineering), which resulted in an MSU Press Release, two articles in The Clarion-Ledger, an article in the Delta Business Journal, and a report on WTVA news.
- **PhD Student Adam Jones Wins *Spirit of State* Award**: During Spring 2009 I nominated my terrific PhD student Adam Jones for several awards. He did not win, but in Spring 2010 I again nominated him for an MSU *Spirit of State* award. He will be presented the award at a ceremony in April.
- **Directed Undergraduate Honors Summer Research Fellowship**: Under my direction, Lorrain Lin, an Honors Undergraduate, wrote a successful Honors Summer Research Fellowship to work in my Mixed Reality Perception Laboratory during Summer 2009. I then continued to work with her Fall 2009 through a directed readings independent study course, and I continue as an informal co-advisor.
- **Directed NASA-Funded Undergraduate Research**: In 2010 I wrote Lorraine Lin into the successful NASA grant "Depth Perception in Near-Field Augmented Reality". Under this grant she worked in the lab during Summer 2010, on the project "Development of Haploscope for Near-Field Depth Perception in Augmented Reality".
- **Advisee Fellowship**: Jeff Carver and I co-advised Chevonne Dancer in CSE PhD program. With our help, she wrote and won a $17,000 Mississippi Space Grant Consortium Fellowship,
Fall 2007 – Summer 2008.
- **New Course Development**: New special topics course Spring 2008: *CSE 4/6990 Computer Game Design* (collaboratively with TJ Jankun-Kelly). Many students asked for this course; it was very popular in Spring 2008, 2009, and 2010.
- **Teaching-Related Grant**: Principal Investigator, "Game Technology for Increasing Interest in Computer Science", 2008 Schilling Special Teaching Project Proposal, *Mississippi State University*, $2,833; July 1, 2008 to June 30, 2009, Co-PI: TJ Jankun-Kelly. This grant purchased computer games and gaming consoles for student gaming projects in this and other courses.
- **PhD Qualifying Exam Mentoring**: In Fall 2008 (Dec 5) I met with PhD students studying for the theory portion of the PhD qualifying exam and discussed correct answers to questions from previous exams. In January 2009 all of these students passed the theory portion of their qualifying exam. During Summer 2010 I have periodically met with PhD students studying for the theory portion of this exam.
- **PhD Qualifying Exam Development**: Developed and graded the following PhD Qualifying Exams:
  (1) CSE Graphics, Spring 2006 (with TJ Jankun-Kelly)
  (2) CPE Algorithms, Spring 2006
  (3) CSE Graphics, Fall 2006 (with TJ Jankun-Kelly)
  (4) CPE Algorithms, Fall 2006
  (5) CSE Graphics, Spring 2007 (with TJ Jankun-Kelly)
  (6) CSE Computer Theory, Fall 2007 (with Susan Bridges)
  (7) CPE Algorithms, Fall 2007
  (8) CSE Computer Theory, Spring 2008 (with Susan Bridges)
  (9) CPE Algorithms, Spring 2008
  (10) CSE Computer Theory, Fall 2008 (with Gene Boggess)
  (11) CPE Algorithms, Fall 2008

(12) CSE Computer Theory, Spring 2009 (with Gene Boggess)
(13) CPE Algorithms, Spring 2009
(14) CSE Computer Theory, Fall 2010 (with Ioana Banicescu)
(15) CPE Discrete Structures, Spring 2010

- **Individual Study Course**: CSE 7000: Computer Forensics Visualization (fall 2007, spring 2008: Josh Franck). *An empirical investigation of the effectiveness of a computer forensics visualization technique.*
- **Individual Study Course**: CSE 7000: Theoretical Analysis of Augmented and Virtual Reality Depth Perception (summer 2010: Josh Franck). *Literature review leading to Experimental Psychology MS thesis.*
- **Individual Study Course**: CSE 8080, CSE 7000: Breakin' and Poppin' (spring 2008, fall 2008: Alexander Morais). *A distributed computer game that runs on both a laptop and the INST display wall; this grew out of a CSE 6990 Computer Game Design final project and became Mr. Morais' MS project*.
- **Individual Study Course**: CSE 7000: Attention in a Driving Simulator (spring 2008: Teena Garrison). *Development of an experimental framework for studying attention while using a cell phone in the CAVS driving simulator. This has become the basis for Ms. Garrison's PhD Thesis project*.
- **Invited Teaching Lecture**: "How to be a Successful Graduate Student: An Advisor's Perspective",
(1) Presentation for MSU Department of Computer Science and Engineering Seminar Class (CSE 8011), *Mississippi State University*, April 1, 2009. Host: Ed Luke.
(2) Presentation to the Applied Cognitive Science Research Seminar, *Mississippi State University*, February 27, 2009. Host: Gary Bradshaw.
(3) Presentation for MSU Department of Computer Science and Engineering Seminar Class (CSE 8011), *Mississippi State University,* November 12, 2008. Host: Susan Bridges.
- **Invited Teaching Lecture**: "Measuring the Effectiveness of Flow Visualization Techniques", Presentation to the Applied Cognitive Science Research Seminar, *Mississippi State University*, February 22, 2008. Host: Deborah Eakin. *This talk featured a discussion of how cognitive science PhD projects could impact ongoing work at the HPC^2*.
- **Served on Design Course Jury:** In Spring 2008 I served on the design projects jury for *ARC 6633 Architecture and Virtual Spaces*. This course is taught in the College of Architecture Art + Design by Anijo Mathew, whose research involves embedding virtual spaces into interior designs. I attended 3 different jury meetings during the semester, and I brought all of Dr. Mathew's students to my Augmented Reality laboratory at the end of the semester.
- **Graduated an External PhD Co-Advisee:** My long-time Virginia Tech collaborator Joe Gabbard, who was a PhD student as well as research faculty, completed his PhD and graduated from Virginia Tech in Fall 2008. Based on my substantial contributions to his dissertation over the years, I was named his dissertation co-advisor.
- **Serving on External PhD Committee**: I am serving on the PhD committee of David O'Gwynn, a PhD student at the University of Alabama at Birmingham. He has visited our lab at Mississippi State and we have exchanged research ideas.

B. Research, creative endeavor, or performances

1. Publications, performances or creative activities:
(For books, indicate date of publication and publisher; for articles, indicate refereed journals; for art shows, indicate judged competition; for musical shows, attach copies of programs; for reports, indicate those done for in-house use.)

Note: *Italicized names* are student co-authors.

Refereed Journal Articles

- T.J. Jankun-Kelly, *Yagneshwara Somayajulu*, **J. Edward Swan II**, "An Evaluation of Glyph Perception for Real Symmetric Traceless Tensor Properties", *Computer Graphics Forum: The International Journal of the Eurographics Association*, (Special Issue on EuroVis 2010), June 2010, Volume 29, Number 3, pages 1133–1142.
- T.J. Jankun-Kelly, *David Wilson*, *Andrew S. Stamps*, *Josh Franck*, Jeffry Carver, **J. Edward Swan II**, "Visual Analysis for Textual Relationships in Digital Forensics Evidence", *Information Visualization*, Special Issue on VizSec 2009, *in press*.

- *Chad A Steed*, Patrick J. Fitzpatrick, **J. Edward Swan II**, T.J. Jankun-Kelly, “Tropical Cyclone Trend Analysis using Enhanced Parallel Coordinates and Statistical Analysis”, *Cartography and Geographic Information Science*, July 2009, Volume 36, Issue 3, pages 251–265.
- *Chad A. Steed*, Patrick J. Fitzpatrick, T.J. Jankun-Kelly, *Amber Yancey*, **J. Edward Swan II**, “An Interactive Parallel Coordinates Technique Applied to a Tropical Cyclone Climate Analysis”, *Computers & Geosciences*, July 2009, Volume 35, Issue 7, pages 1529–1539.
- *Joseph L. Gabbard*, **J. Edward Swan II**, “Usability Engineering for Augmented Reality: Employing User-based Studies to Inform Design”, *IEEE Transactions on Visualization and Computer Graphics*, May/June 2008, Volume 14, Number 3, pages 513–525.
- *Joel P. Martin*, **J. Edward Swan II**, Robert J. Moorhead II, Zhanping Liu, *Shangshu Cai*, “Results of a User Study on 2D Hurricane Visualization”, *Computer Graphics Forum: The International Journal of the Eurographics Association (Special Issue of EuroVis 2008)*, May 2008, Volume 27, Number 3, Pages 991–998.
- **J. Edward Swan II**, *Adam Jones*, *Eric Kolstad*, Mark A. Livingston, Harvey S. Smallman, “Egocentric Depth Judgments in Optical, See-Through Augmented Reality”, *IEEE Transactions on Visualization and Computer Graphics*, Volume 13, Number 3, May/June 2007, pages 429–442. **Winner of the 2008 Bagley College of Engineering Outstanding Research Paper Award**.
- Greg Schmidt, Dennis G. Brown, *Erik B. Tomlin*, **J. Edward Swan II**, Yohan Baillot, “Probabilistic Algorithms, Integration, and Empirical Evaluation for Disambiguating Multiple Selections in Frustum-Based Pointing”, *Journal of Multimedia*, Volume 1, Issue 3, June 2006, pages 1–12.
- *Joseph L. Gabbard*, **J. Edward Swan II**, Deborah Hix, “The Effects of Text Drawing Styles, Background Textures, and Natural Lighting on Text Legibility in Outdoor Augmented Reality”, *PRESENCE: Teleoperators and Virtual Environments*, Volume 15, Number 1, February 2006, pages 16–32.

Refereed Conference Publications

Note: In my professional community, these full-text refereed conference articles have very low acceptance rates (listed for each article), are widely read, and have a professional impact that is comparable to journal articles.

- Ernst Kruijff, **J. Edward Swan II**, Steve Feiner, “Perceptual Issues in Augmented Reality Revisited”, (to appear in) *Technical Papers*, *IEEE International Symposium on Mixed and Augmented Reality* (ISMAR 2010), Seoul, Korea, October 13–16, 2010, Acceptance rate: 22% (24 out of 107).
- *Gurjot Singh*, **J. Edward Swan II**, *J. Adam Jones*, Stephen R. Ellis, “Depth Judgment Measures and Occluding Surfaces in Near-Field Augmented Reality”, *Proceedings of the Symposium on Applied Perception in Graphics and Visualization* (APGV 2010), Los Angeles, California, USA, July 23–24, 2010, pages 149–156, Acceptance rate: 56% (27 out of 48).
- Joseph L. Gabbard, *Jason Zedlitz*, **J. Edward Swan II**, Woodrow W. Winchester III, “More Than Meets the Eye: An Engineering Study to Empirically Examine the Blending of Real and Virtual Color Spaces”, *Technical Papers*, *Proceedings of IEEE Virtual Reality 2010*, Waltham, Massachusetts, USA, March 20–24, pages 79–86, Acceptance rate: 19%.
- T.J. Jankun-Kelly, *David Wilson*, *Andrew S. Stamps*, *Josh Franck*, Jeffery Carver, **J. Edward Swan II**, “A Visual Analytic Framework for Exploring Relationships in Textual Contents of Digital Forensics Evidence”, (to appear in) *Proceedings of Workshop on Visualization for Cyber Security* (VizSec 2009), October, 2009, Acceptance rate: 43%.
- *Chad A. Steed*, **J. Edward Swan II**, T.J. Jankun-Kelly, Patrick J. Fitzpatrick, “Guided Analysis of Hurricane Trends Using Statistical Processes Integrated with Interactive Parallel Coordinates”, (to appear in) Proceedings of the *IEEE Symposium on Visual Analytics Science and Technology* (VAST 2009), Atlantic City, New Jersey, USA, October 12–13, Acceptance rate: 38%.
- *Eric Klein*, **J. Edward Swan II**, Gregory S. Schmidt, Mark A. Livingston, Oliver G. Staadt, “Measurement Protocols for Medium-Field Distance Perception in Large-Screen Immersive Displays”, *Technical Papers, Proceedings of IEEE Virtual Reality 2009*, Lafayette, Louisiana, USA, March 14–18, pages 107–113, Acceptance rate: 28%.
- Mark A. Livingston, Zhuming Ai, **J. Edward Swan II**, Harvey S. Smallman, “Indoor vs. Outdoor Depth Perception for Mobile Augmented Reality”, *Technical Papers, Proceedings of IEEE Virtual Reality 2009*, Lafayette, Louisiana, USA, March 14–18, pages 55–61, Acceptance rate: 28%.

- *J. Adam Jones*, **J. Edward Swan II**, *Gurjot Singh*, *Eric Kolstad*, Stephen R. Ellis, “The Effects of Virtual Reality, Augmented Reality, and Motion Parallax on Egocentric Depth Perception”, *Proceedings of the Symposium on Applied Perception in Graphics and Visualization*, Los Angeles, California, USA, August 9–10, 2008, pages 9–14. Acceptance rate: 55%.
- T.J. Jankun-Kelly, *Josh Franck*, *David Wilson*, Jeffrey Carver, David Dampier, **J. Edward Swan II**, “Show Me How You See: Lessons from Studying Computer Forensics Experts for Visualization”, *Proceedings of the Fifth International Workshop on Visualization for Computer Security* (VizSEC 2008), Cambridge, Massachusetts, USA, September 15, 2008, pages 80–86. Acceptance Rate: 67%.
- *Joseph L. Gabbard*, **J. Edward Swan II**, Deborah Hix, *Si-Jung Kim*, *Greg Fitch*, “Active Text Drawing Styles for Outdoor Augmented Reality: A User-Based Study and Design Implications”, *Technical Papers*, *Proceedings of IEEE Virtual Reality 2007*, Alexandria, Virginia, USA, March 25–29, pages 35–42. Acceptance rate: 20%.
- **J. Edward Swan II**, Mark A. Livingston, Harvey S. Smallman, Dennis Brown, Yohan Baillot, *Joseph L. Gabbard*, Deborah Hix, “A Perceptual Matching Technique for Depth Judgments in Optical, See-Through Augmented Reality”, *Technical Papers*, *Proceedings of IEEE Virtual Reality 2006*, Alexandria, Virginia, USA, March 25–29, pages 19–26. Acceptance rate: 28%. **Winner of an “Honorable Mention” award at IEEE Virtual Reality 2006.** Award rate: 11%.
- Greg Schmidt, Dennis G. Brown, *Erik B. Tomlin*, **J. Edward Swan II**, Yohan Baillot, “Toward Disambiguating Multiple Selections for Frustum-Based Pointing”, *Technical Papers*, *Proceedings of the 1st IEEE Symposium on 3D User Interfaces 2006*, Alexandria, Virginia, USA, March 25–26, 2006, pages 87–94. Acceptance rate: 33%.
- *Joseph L. Gabbard*, **J. Edward Swan II**, Deborah Hix, Robert S. Schulman, *John Lucas*, *Divya Gupta*, “An Empirical User-Based Study of Text Drawing Styles and Outdoor Background Textures for Augmented Reality”, *Technical Papers*, *Proceedings of IEEE Virtual Reality 2005*, Bonn, Germany, March 12–16, 2005, IEEE Computer Society, pages 11–18. Acceptance rate: 26%. (April 2006: Nominated for College of Engineering Research Paper of the Year by CSE department).

<u>Non-Refereed Conference Abstracts, Short Papers, and Posters</u>

- Chad A. Steed, T.J. Jankun-Kelly, **J. Edward Swan II**, Robert J. Moorhead, “Illustrative Visualization of Hurricane Advisory Information”, *Poster Compendium*, *Proceedings of IEEE Visualization 2009*, Atlantic City, New Jersey, USA, October 11–16, 2009.
- Chad A. Steed, T.J. Jankun-Kelly, **J. Edward Swan II**, Robert J. Moorhead, “Illustrative Visualization Techniques for Hurricane Advisory Information”, *Proceedings of the Oceans ’09 MTS/IEEE Biloxi Technical Program*, October 26–29, 2009, Biloxi, MS, USA.
- *Gurjot Singh*, **J. Edward Swan II**, J. *Adam Jones*, *Lorraine Lin*, Stephen R. Ellis, “Depth Judgment Measures and Occluders in Near-Field Augmented Reality”, *Poster Compendium*, *Proceedings of Symposium on Applied Perception in Graphics and Visualization* (APGV 2009), Chania, Crete, Greece, September 30–October 2, 2009, page 127.
- *J. Adam Jones*, **J. Edward Swan II**, *Gurjot Singh*, *Josh Franck*, Stephen R. Ellis, “The Effects of Continued Exposure to Medium Field Augmented and Virtual Reality on the Perception of Egocentric Depth”, *Poster Compendium*, *Proceedings of Symposium on Applied Perception in Graphics and Visualization* (APGV 2009), Chania, Crete, Greece, September 30–October 2, 2009, page 138.
- *Chad A. Steed*, Patrick J. Fitzpatrick, T.J. Jankun-Kelly, **J. Edward Swan II**, “North Atlantic Hurricane Trend Analysis using Parallel Coordinates and Statistical Techniques”, Workshop on Geo-Spatial Visual Analytics 2008, *Fifth International Conference on Geographic Information Science*, September 23–26, Park City, Utah, USA.
- *Adam Jones*, **J. Edward Swan II**, *Gurjot Singh*, *Eric Kolstad*, “The Effects of Virtual Reality, Augmented Reality, and Motion Parallax on Egocentric Depth Perception”, *Poster Compendium*, *Proceedings of IEEE Virtual Reality 2008*, Reno, Nevada, USA, March 8–12, 2008, pages 267–268.
- Joseph J. LaViola Jr., Doug A. Bowman, Stephen R. Ellis, Victoria Interrante, Benjamin C. Lok, **J. Edward Swan II**, “User Studies in VR: What Can We Learn From Them and What Are They Good For?”, *Panels*, *Proceedings of IEEE Virtual Reality 2008*, Reno, Nevada, USA, March 8–12, 2008, pages 303–304.
- *Chad Steed*, Patrick Fitzpatrick, T.J. Jankun-Kelly, *Amber Yancey*, **J. Edward Swan II**, “Practical Applications of Parallel Coordinates to Hurricane Trend Analysis”, *Poster Compendium*, *Proceedings of IEEE Visualization 2007*, Sacramento, California, USA, October 28 – November 1, 2007.

- Victoria Interrante, Joseph K. Kearney, Dennis Proffitt, **J. Edward Swan II**, William B. Thompson, "Spatial Perception in Immersive Virtual Environments: New Theories and Current Controversies", *Panels*, *Proceedings of IEEE Virtual Reality 2007*, Charlotte, North Carolina, USA, March 10–14, pages 315–316.
- *Eric Klein*, Oliver Staadt, **J. Edward Swan II**, Greg Schmidt, Mark Livingston, "Egocentric Medium-Field Distance Perception in Projection Environments", Poster Paper, *Proceedings of Symposium on Applied Perception in Graphics and Visualization* (APGV 2006), Boston, Massachusetts, USA, July 28–29, 2006, page 147.
- **J. Edward Swan II**, *Joseph L. Gabbard*, "Survey of User-Based Experimentation in Augmented Reality", *Proceedings of 1st International Conference on Virtual Reality*, *HCI International 2005*, Las Vegas, Nevada, USA, July 22–27, 2005.
- Mark A. Livingston, *Catherine Zanbaka*, **J. Edward Swan II**, Harvey S. Smallman, "Objective Measures for the Effectiveness of Augmented Reality", *Poster Papers*, *Proceedings of IEEE Virtual Reality 2005*, Bonn, Germany, March 12–16, 2005, IEEE Computer Society, pages 287–288.
- Mark A. Livingston, Dennis Brown, **J. Edward Swan II**, Brian Goldiez, Yohan Baillot, Simon J. Julier, Greg S. Schmidt, "Applying a Testing Methodology for Augmented Reality Interfaces to Simulation Systems", *2005 International Conference on Human-Computer Interface Advances for Modeling and Simulation* (SIMCHI '05), New Orleans, Louisiana, USA, January 23–25, 2005.
- Mark A. Livingston, **J. Edward Swan II**, Simon J. Julier, Yohan Baillot, Dennis Brown, Lawrence J. Rosenblum, *Joseph L. Gabbard*, Tobias H. Höllerer, Deborah Hix, "Evaluating System Capabilities and User Performance in the Battlefield Augmented Reality System", *Performance Metrics for Intelligent Systems Workshop* (PerMIS '04), Gaithersburg, Maryland, USA, August 24–26, 2004.

2. Professional papers read; indicate whether invited, refereed, or volunteered.
   Cite organization, date, and title:

- (*invited*) **J. Edward Swan II**, "Depth Perception in Augmented Reality: From AR Technology to Perceptual Science", Presentation to the *Hank Virtual Environments Lab*, *University of Iowa*, June 14, 2010. Host: Joe Kearney.
- (*invited*) **J. Edward Swan II**, "Depth Perception in Augmented Reality: From AR Technology to Perceptual Science", Presentation to the *Visual Space Perception Laboratory, University of California, Berkeley*, March 12, 2010. Host: Martin S. Banks.
- (*invited*) **J. Edward Swan II**, "Depth Perception in Augmented Reality: From AR Technology to Perceptual Science", Presentation to the *Human Systems Integration Division*, *National Aeronautics and Space Administration* (NASA), March 11, 2010. Host: Stephen R. Ellis.
- (*invited*) **J. Edward Swan II**, "Empirically Evaluating a Hyperspectral Image Visualization Method: What Does Effectiveness Really Mean?", Presentation at the *Naval Research Laboratory*, *Stennis Space Center* (NRLSSC), May 7, 2009. Host: Chad Steed.
- (*invited*) **J. Edward Swan II**, "Conducting Human-Subject Experiments", Presentation for Virtual Reality and Level-of-Detail Class (Electrical and Computer Engineering), *Mississippi State University*, April 16, 2009. Host: Phil Amburn.
- (*invited*) **J. Edward Swan II**, "How to be a Successful Graduate Student: An Advisor's Perspective", Presentation for Department of Computer Science and Engineering Seminar Class (CSE 8011), *Mississippi State University*, April 1, 2009. Host: Ed Luke.
- (*refereed*) **J. Edward Swan II**, "Measurement Protocols for Medium-Field Distance Perception in Large-Screen Immersive Displays", Presentation at *IEEE Virtual Reality 2009*, Lafayette, Louisiana, USA, March 18, 2009. Host: Dirk Reiners.
- (*invited*) **J. Edward Swan II**, "How to be a Successful Graduate Student: An Advisor's Perspective", Presentation to the Applied Cognitive Science Research Seminar, *Mississippi State University*, February 27, 2009. Host: Gary Bradshaw.
- (*invited*) **J. Edward Swan II**, "How to be a Successful Graduate Student: An Advisor's Perspective", Presentation for Department of Computer Science and Engineering Seminar Class (CSE 8011), *Mississippi State University*, November 12, 2008. Host: Susan Bridges.

- (*invited*) **J. Edward Swan II**, “Augmented Reality: Technology and Research Challenges”, Presentation to Vice Commander Brigadier General (select) Tony Buntyn and Major Tim Franz, US Air Force Cyber Command, *Mississippi State University*, March 19, 2008. Host: Rayford B. Vaughn.
- (*refereed*) Joseph J. LaViola Jr., Doug A. Bowman, Stephen R. Ellis, Victoria Interrante, Benjamin C. Lok, **J. Edward Swan II**, “User Studies in VR: What Can We Learn From Them and What Are They Good For?”, Panel Presentation at IEEE Virtual Reality 2007, Reno, Nevada, USA, March 10, 2008. Panel Organizer: Joseph J. LaViola Jr.
- (*invited*) **J. Edward Swan II**, “Measuring the Effectiveness of Flow Visualization Techniques”, Presentation to the Applied Cognitive Science Research Seminar, *Mississippi State University*, February 22, 2008. Host: Deborah Eakin.
- (*refereed*) Victoria Interrante, Dennis Proffitt, William Thompson, **J. Edward Swan II**, Joe Kearney, “Spatial Perception in Immersive Virtual Environments: New Theories and Current Controversies”, Panel presentation at *IEEE Virtual Reality 2007*, Charlotte, North Carolina, USA, March 13, 2007. Panel Organizer: Victoria Interrante.
- (*invited*) **J. Edward Swan II**, “Augmented Reality: Technology and Research Challenges”, Presentation at the Security Awareness Briefing, sponsored by the Mississippi Infragard Program and the National Classification Management Society Magnolia Chapter, *Mississippi State University*, April 12, 2006. Host: David Dampier.
- (*refereed*) **J. Edward Swan II**, “A Perceptual Matching Technique for Depth Judgments in Optical, See-Through Augmented Reality”, Presentation at *IEEE Virtual Reality 2006*, Alexandria, Virginia, USA, March 27, 2006. Host: Benjamin Lok.
- (*volunteered*) **J. Edward Swan II**, “Adaptation, Depth Perception, and X-Ray Vision in Optical, See-Through Augmented Reality”, Presentation for MSU Department of Computer Science and Engineering Seminar Class (CSE 8011), *Mississippi State University*, November 11, 2005. Host: Ioana Banicescu.
- (*volunteered*) **J. Edward Swan II**, “Depth Judgments in Optical, See-Through Augmented Reality”, Presentation to the Applied Cognitive Science Research Seminar, *Mississippi State University*, October 7, 2005. Host: Carrick Williams.
- (*invited*) **J. Edward Swan II**, “Adaptation, Depth Perception, and X-Ray Vision in Optical, See-Through Augmented Reality”, Invited seminar presentation at *NASA Ames Research Laboratory*, Moffett Field, California, USA, July 28, 2005. Hosts: Steve Ellis, Bernard Adelstein.
- (*invited*) **J. Edward Swan II**, “Survey of User-Based Experimentation in Augmented Reality”, Presentation at *HCI International 2005*, Las Vegas, Navada, USA, July 25, 2005. Host: Deborah Hix.
- (*volunteered*) **J. Edward Swan II**, “Depth Perception and X-Ray Vision in Optical, See-Through Augmented Reality”, Inaugural Presentation of the Institute for Neurocognitive Science and Technology (INST) Seminar Series (the first ever INST seminar), *Mississippi State University*, April 20, 2005. Host: Stephanie Doane.
- (*refereed*) **J. Edward Swan II**, “An Empirical User-Based Study of Text Drawing Styles and Outdoor Background Textures for Augmented Reality”, Presentation at *IEEE Virtual Reality 2005*, Bonn, Germany, March 14, 2005. Host: Benjamin Lok.
- (*volunteered*) **J. Edward Swan II**, “Depth Perception in Augmented Reality: Initial Results”, Presentation for MSU Department of Computer Science and Engineering seminar class (CSE 8011), *Mississippi State University*, November 10, 2004. Host: Susan Bridges.
- (*invited*) **J. Edward Swan II**, “Graphics and Visualization, Augmented and Virtual Reality”, Presentation for meeting of representatives from Computer Science and Engineering (CSE) and the U.S. Army Engineer Research and Development Center / Information Technology Laboratory (ERDC/ITL), *Mississippi State University*, October 28, 2004. Host: Julia Hodges.
- (*invited*) **J. Edward Swan II**, “Augmented Reality: Potential Applications and Research Challenges”, Presentation at the National Science Foundation Industry / University Cooperative Research Center Organizational Meeting, *Mississippi State University*, Mississippi, September 22, 2004. Host: Ray Vaughn.

3. Grants for research or study:

Proposals submitted since last promotion and total dollar amount: __26__; $25,703,351[1]

- (*unsuccessful*) Song Zhang, Jamie Dyer, Andrew E. Mercer, **J. Edward Swan II** (Principal Investigators), "Uncertainty Visualization for High Dimensional Multivariate Data in Meteorology", The *National Science Foundation* (NSF) CCF Foundations of Visual Analytics. $444,407; May 16, 2010 to May 15, 2013.
- (*successful*) **J. Edward Swan II**, "Depth Perception in Near-Field Augmented Reality", *The Mississippi Space Grant Consortium, National Aeronautics and Space Administration* (NASA). $49,138; January 10, 2010 to January 9, 2011.
- (*successful*) **J. Edward Swan II** (Principal Investigator), "HCC: Small: Depth Perception in Near- and Medium-Field Augmented Reality", The *National Science Foundation* (NSF) IIS Human-Centered Computing. $499,998; October 1, 2010 to September 30, 2013.
- (*unsuccessful*) Joseph L. Gabbard, **J. Edward Swan II** (Principal Investigators), "HCC: Small: Collaborative Research: Color Perception in Augmented Reality", The *National Science Foundation* (NSF) IIS Human-Centered Computing. $298,953 to Virginia Tech, $199,046 to Mississippi State; October 1, 2010 to September 30, 2013.
- (*unsuccessful*) T.J. Jankun-Kelly, **J. Edward Swan II**, Jeffrey C. Carver (Principal Investigators), "TC: Small: Collaborative Research: Improving the Usability of Computer Forensics and Security via Empirically-based Visualization", The *National Science Foundation* (NSF) CNS Trustworthy Computing. $349,998 to Mississippi State, $148,410 to University of Alabama. August 15, 2010 to August 14, 2013.
- (*unsuccessful*) T.J. Jankun-Kelly, **J. Edward Swan II** (Principal Instigators), "Game Technology for Increasing Interest in Computer Science: Continuation", 2009 Schilling Special Teaching Project Proposal, *Mississippi State University*, $3,000; July 1, 2009 to June 30, 2010.
- (*unsuccessful*) Bindu Nanduri, Fiona McCarthy, Mahalingam Ramkumar (Project Investigators); **J. Edward Swan II**, Changhe Yuan, Andy D. Perkins, T.J. Jankun-Kelly (Senior Personnel), "Modeling Interspecies Interactions: Bovine Respiratory Disease Complex", The *National Science Foundation* (NSF). $3,100,202. The pre-proposal was accepted, but a full proposal was not encouraged. Summer 2009.
- (*successful*) T.J. Jankun-Kelly, **J. Edward Swan II** (Principal Instigators), "Game Technology for Increasing Interest in Computer Science", 2008 Schilling Special Teaching Project Proposal, *Mississippi State University*, $2,833; July 1, 2008 to June 30, 2009.
- (*unsuccessful*) T.J. Jankun-Kelly, **J. Edward Swan II** (Principal Investigators), "An Empirical Study of Perceptually-Motivated Illustrative Rendering for Information Visualization", The *National Science Foundation* (NSF) CPA Program. $433,653; October 2008 to September 2011.
- (*unsuccessful*) Fiona McCarthy, Susan Bridges, **J. Edward Swan II** (Principal Investigators), "Gene Ontology Annotations and Educational Resources for Pig Research", United States Department of Agriculture (USDA). $794,052; July 2008 to June 2011.
- (*unsuccessful*) T.J. Jankun-Kelly, **J. Edward Swan II** (Principal Investigators), "An Empirical Study of Perceptually-Motivated Illustrative Rendering for Information Visualization", The *National Science Foundation* (NSF) CPA Program. $372,823; October 2007 to September 2010.
- (*successful*) **J. Edward Swan II** (Principal Investigator), "Egocentric Depth Perception in Augmented Reality", The *National Science Foundation* (NSF) IIS Human-Centered Computing. $392,268; October 2007 to September 2010.
- (*unsuccessful*; *pre-proposal*) T.J. Jankun-Kelly, **J. Edward Swan II** (Principal Investigators), "Visualization Services for Large-Scale System Defense", *Air Force NICECAP Program* (DoD). $350,000; January 2007 to June 2008.
- (*successful*) T.J. Jankun-Kelly, Jeff Carver, Dave Dampier, **J. Edward Swan II** (Principal Investigators), "CT-ISG: Empirically-Based Visualization for Computer Security and Forensics", The *National Science Foundation* (NSF) CNS CyberTrust. $300,000; October 1, 2006 to September 30, 2009.

[1] I participated in a large, multi-center proposal (unsuccessful), which called for $16M that would have gone to institutions besides MSU. The total dollar amount of all my proposals that would have come to MSU is $11,352,283.

- (*unsuccessful*) **J. Edward Swan II** (Principal Investigator), "Vibration-Stabilizing Information Displays During Launch with Augmented Reality Technology", *ASEE NASA Faculty Fellowship Program*. $14,000; April 2006 to September 2006.
- (*successful*) **J. Edward Swan II**, Stephen R. Ellis (Principal Investigators), "Vibration-Stabilizing Information Displays During Launch with Augmented Reality Technology", submitted to *The Mississippi Space Grant Consortium, National Aeronautics and Space Administration* (NASA), February 2006. $42,846; April 1, 2006 to March 31, 2007.
- (*successful*) Jeff Carver, **J. Edward Swan II** (Principal Investigators), "Time-Domain Visualization of Software Source Code and Lifecycle Documents", submitted to *The Center for Computer Security Research (CCSR), Mississippi State University*, December 2005. $20,000; January 1, 2006 to August 31, 2006.
- (*successful*) **J. Edward Swan II** (Principal Investigator), "Depth Perception in Augmented Reality", submitted to 2006 Research Initiation Program, *The Office of Research*, *Mississippi State University*, October 2005. $10,000; January 1, 2006 to December 31, 2006.
- (*unsuccessful*) **J. Edward Swan II**, Stephanie Doane, T.J. Jankun-Kelly (Principal Investigators), "Building the Human Systems Research Display Wall (HSRWall)", submitted to *Office of Naval Research*, September 2005. $394,745; April 1, 2006 to March 31, 2007.
- (*unsuccessful*; *pre-proposal*) **J. Edward Swan II** (MSU), Harvey S. Smallman (Pacific Science and Engineering LLC), Mark Livingston (Naval Research Lab) (Principal Investigators), "Depth Perception and X-Ray Vision in Augmented Reality", submitted to *Office of Naval Research*, June 2005. $339,000; October 1, 2005 to September 30, 2008.
- (*successful*) Robert J. Moorhead, **J. Edward Swan II** (Principal Investigators), "High Performance Computing Visualization Initiative: Visualization User Studies", *Department of the Army* (DoD) (subcontract; Jackson State University prime contractor), $149,944; August 15, 2005 to June 30, 2007.
- (*successful*) T.J. Jankun-Kelly (MSU), **J. Edward Swan II** (MSU) (Principal Investigators), "Acquisition of a Display Wall for Human Systems Research and Biological Imaging", submitted to the *National Science Foundation*, 1-27-05, $864,026; August 1, 2005 to July 31, 2008.
- (*unsuccessful*) Robert L. Hester (University of Mississippi Medical Center; Principal Investigator); **J. Edward Swan II** (Co-Investigator; there are 9 additional co-investigators), "National Center for Physiological and Clinical Simulation", submitted to the *National Institutes of Health*, January 2005, Total value: $16,055,104; value to MSU: $1,801,401; October 1, 2005 to September 30, 2010.
- (*unsuccessful*): Yogindar Dandass (MSU), **J. Edward Swan II** (MSU), Sungbum Hong (Jackson State University) (Principal Investigators), "Stochastic Scheduling for Soft Real-Time Parallel Applications", submitted to the *National Science Foundation*, 11-23-04, $361,002, August 16, 2005 to August 15, 2008.
- (*unsuccessful*) **J. Edward Swan II** (MSU), Harvey Smallman (Pacific Science and Engineering LLC) (Principal Investigators), "Depth Perception in Augmented Reality", submitted to *Office of Research, Mississippi State University*, 9-20-04, $10,000, January 1, 2005 to December 31, 2005.
- (*successful*) **J. Edward Swan II** (Principal Investigator), "Building An Infrastructure for Augmented Reality Perceptual Research and Engineering at the INST", submitted to *The Office of Naval Research* (ONR), a seed grant through the Institute for Neurocognitive Science and Technology (INST), August 2004. $53,901, January to December 2005.

Proposals funded (cite source, title of project, role [PI, etc.], $ amount, dates): _11_; $1,945,271

- **J. Edward Swan II** (Role: PI), "HCC: Small: Depth Perception in Near- and Medium-Field Augmented Reality" (IIS-1018413), The *National Science Foundation* (NSF), Information and Intelligent Systems (IIS), Human-Centered Computing (HCC), $499,998; October 1, 2010 to September 30, 2013.
- **J. Edward Swan II** (Role: PI), "Depth Perception in Near-Field Augmented Reality", *The Mississippi Space Grant Consortium, National Aeronautics and Space Administration* (NASA). $49,138; January 10, 2010 to January 9, 2011.
- T.J. Jankun-Kelly, **J. Edward Swan II** (Role: Co-PI), "Game Technology for Increasing Interest in Computer Science", 2008 Schilling Special Teaching Project Proposal, *Mississippi State University*, $2,833; July 1, 2008 to June 30, 2009.

- **J. Edward Swan II** (Role: PI), "Egocentric Depth Perception in Augmented Reality", The *National Science Foundation* (NSF) IIS Human-Centered Computing. $392,268; October 2007 to September 2010.
- T.J. Jankun-Kelly, Jeff Carver, Dave Dampier, **J. Edward Swan II** (Role: Co-PI), "CT-ISG: Empirically-Based Visualization for Computer Security and Forensics", The *National Science Foundation* (NSF) CNS CyberTrust. $300,000; October 1, 2006 to September 30, 2009. Role: Co-PI.
- **J. Edward Swan II**, Stephen R. Ellis (Role: PI), "Vibration-Stabilizing Information Displays during Launch with Augmented Reality Technology", *The Mississippi Space Grant Consortium, National Aeronautics and Space Administration* (NASA). $42,846; April 1, 2006 to March 31, 2007.
- Jeff Carver, **J. Edward Swan II** (Role: Co-PI), "Time-Domain Visualization of Software Source Code and Lifecycle Documents", *The Center for Computer Security Research (CCSR), Mississippi State University*. $20,000; January 1, 2006 to August 31, 2006.
- **J. Edward Swan II** (Role: PI), "Depth Perception in Augmented Reality", 2006 Research Initiation Program, *The Office of Research, Mississippi State University*. $10,000; January 1, 2006 to December 31, 2006.
- Robert J. Moorhead, **J. Edward Swan II** (Role: Co-PI), "High Performance Computing Visualization Initiative: Visualization User Studies", *Department of the Army* (DoD) (subcontract; Jackson State University prime contractor), $149,944; August 15, 2005 to June 30, 2007.
- T.J. Jankun-Kelly, **J. Edward Swan II** (Role: Co-PI), "Acquisition of a Display Wall for Human Systems Research and Biological Imaging", The *National Science Foundation* (NSF), CNS0521564 05080745. $425,487; August 1, 2005 to July 31, 2008.
- **J. Edward Swan II** (Role: PI), "Building An Infrastructure for Augmented Reality Perceptual Research and Engineering at the INST", The *Office of Naval Research* (ONR), a seed grant through the *Institute for Neurocognitive Science and Technology* (INST) under the ONR grant "Optimizing Adaptive Warrior Performance", MSU 006252-005 (subcontract of ONR N000140410341). $52,757; January 2005 to May 2006.

4. Other:

<u>Patent Application</u>

- *Chad A. Steed*, **J. Edward Swan II**, T.J. Jankun-Kelly, Patrick J. Fitzpatrick, "Parallel Coordinates Analytic Toolkit for Multivariate Data Analysis", *Provisional Application for Patent*, Docket Number 99713-US1, Application Number 61146717, Filed January 2009.

C. <u>Service</u>

1. Public service, as lectures, short courses, workshops (with dates, organizations, places):

Since 2004, I have organized and led a series of professional tutorials on the topic of conducting human-subject experiments. I have offered these tutorials at both the IEEE Virtual Reality and the IEEE Visualization conferences. My co-presenters have been some of my longtime collaborators from NASA Ames Laboratory and the Naval Research Laboratory. Since my arrival at MSU, organizing and leading these tutorials has been my primary professional service activity.

- **J. Edward Swan II**, Bernard D. Adelstein, Joseph L. Gabbard, "Conducting Human-Subject Experiments with Virtual and Augmented Reality", Tutorial presented at *IEEE Virtual Reality 2009*, Lafayette, LA, USA, March 15, 2009. Course Organizer: **J. Edward Swan II**.
- **J. Edward Swan II**, Mark A. Livingston, "Experimental Design and Analysis for Human-Subject Visualization Experiments", Tutorial presented at *IEEE Visualization 2008*, Columbus, OH, USA, October 20, 2008. Course Organizer: **J. Edward Swan II**.
- **J. Edward Swan II**, "Experimental Design and Analysis for Human-Subject Visualization Experiments", Tutorial presented at *IEEE Visualization 2007*, Sacramento, CA, USA, October 28, 2007. Course Organizer: **J. Edward Swan II**.
- **J. Edward Swan II**, Stephen R. Ellis, Bernard D. Adelstein, "Conducting Human-Subject Experiments with Virtual and Augmented Reality", Tutorial presented at *IEEE Virtual Reality 2007*, Charlotte, NC, USA, March 10, 2007. Course Organizer: **J. Edward Swan II**.

- **J. Edward Swan II**, “Experimental Design and Analysis for Human-Subject Visualization Experiments”, Tutorial presented at *IEEE Visualization 2006*, Baltimore, MD, USA, October 30, 2006. Course Organizer: **J. Edward Swan II**.
- **J. Edward Swan II**, Stephen R. Ellis, Bernard D. Adelstein, “Conducting Human-Subject Experiments with Virtual and Augmented Reality”, Tutorial presented at *IEEE Virtual Reality 2006*, Washington, DC, USA, March 25, 2006. Course Organizer: **J. Edward Swan II**.
- Katerina Mania, Heinrich Bulthoff, Douglas Cunningham, Bernard D. Adelstein, Hyung Seok Kim, Nick Mourkoussis, Tom Troscianko, **J. Edward Swan II**, “Human-Centered Fidelity Metrics for Virtual Environment Simulation”, Tutorial presented at *IEEE Virtual Reality 2005*, Bonn, Germany, March 12, 2005. Course Organizer: Katerina Mania.

2. Professional association service (offices held, journals edited, etc.):

<u>Review Panels</u>

- *National Science Foundation* (NSF) review panel, Washington DC, April 2010.
- *IEEE Virtual Reality 2010* International Program Committee, Waltham, Massachusetts, USA, March 20–24, 2010.
- Served on *Naval Research Laboratory External Review Panel*, Battlespace Environments and Undersea Warfare Focus Areas (6.1 / 6.2) Marine Geosciences Research Program, Stennis Space Center, MS, USA, July 28–30, 2009.
- Served on *International Symposium on Mixed and Augmented Reality* (ISMAR 2009) Science & Technology Area Chair (attended program committee meeting), Orlando, FL, USA, July 16–17, 2009.
- Served on *National Science Foundation* (NSF) review panel, Washington DC, September 2008.
- Served on *National Science Foundation* (NSF) review panel, Washington DC, January 2008.
- Served on *National Science Foundation* (NSF) review panel, Washington DC, October 2007.
- Served on *IEEE Virtual Reality 2006* Program Review Committee and International Program Committee, chaired by Bernd Froehlich, Monterey CA, November 2005.
- Served on *National Science Foundation* (NSF) review panel, Washington DC, June 2005.
- Served on *National Science Foundation* (NSF) review panel, Washington DC, June 2005. (Served on two separate panels during the same month.)
- Served on *National Science Foundation* (NSF) review panel, Washington DC, June 2005.
- Served on *IEEE Virtual Reality 2005* Program Review Committee, chaired by Bernd Froehlich, Washington DC, November 2004.

<u>Program and Conference Committees</u>

- Serving as *Search Committee Member* for the Editor-in-Chief of *IEEE Transactions on Visualization and Computer Graphics*, August–September 2010.
- Serving as *IEEE Virtual Reality 2011* posters co-chair, Singapore, March 2011.
- Serving on *International Workshop on Mobile Collaborative Augmented Reality* program committee, held in conjunction with ISMAR 2010, Seoul, Korea, October 13–16, 2010.
- Served on *International Symposium on Mixed and Augmented Reality 2010* (ISMAR 2010) program committee, Seoul, Korea, October 13–16, 2010.
- Served on *ACM Symposium on Virtual Reality and Software Technology 2010* (VRST 2010) program committee.
- Served on *Applied Perception in Graphics and Visualization 2010* (APGV 2010) program committee.
- Served as *Session Chair*, “Papers Session 1: AR Studies”, *IEEE Virtual Reality 2010*, Waltham, Massachusetts, USA, March 22, 2010.

- Served as *Posters Fast-Forward Chair*, *IEEE Virtual Reality 2010*, Waltham, Massachusetts, USA, March 22, 2010.
- Served on *IEEE Virtual Reality 2010* International Program Committee, Waltham, Massachusetts, USA, March 20–26, 2010.
- Served as *IEEE Virtual Reality 2010* posters co-chair, Waltham, MS, USA, March 2010.
- Served on *International Symposium on Visual Computing* 2010 (ISVC 2010).
- Served on *Conference on Visualization and Data Analysis 2010* (VDA 2010) program committee.
- Served on *ACM Symposium on Virtual Reality and Software Technology 2009* (VRST 2009) program committee.
- Served on *International Symposium on Visual Computing 2009* (ISVC09) program committee.
- Served on *Conference on Visualization and Data Analysis 2009* (VDA 2009) program committee.
- Served on *Conference on Visualization and Data Analysis 2008* (VDA 2008) program committee.
- Served on International Program Committee for the *International Symposium on Mixed and Augmented Reality 2007* (ISMAR 2007).
- Served as *Session Chair*, “Papers 2: 3DUI & AR/VR Systems”, IEEE Virtual Reality 2007, Charlotte, North Carolina, USA, March 12, 2007.
- Served on *Conference on Visualization and Data Analysis 2007* (VDA 2007) program committee.
- Served on *IEEE Virtual Reality 2007* International Program Committee, Charlotte, North Carolina, USA, March 10–14, 2007.
- Served as *IEEE Virtual Reality 2006* workshops committee co-chair.
- Served on *IEEE Virtual Reality 2006* International Program Committee, Arlington, Virginia, USA, March 25–29, 2006.
- Served on *International Symposium on Visual Computing 2006* (ISVC06) program committee.
- Served as *session chair* “Session 5: Evaluation and Perception”, *IEEE Virtual Reality 2006*, Alexandria, Virginia, USA, March 28, 2006.
- Served on *Conference on Visualization and Data Analysis 2006* (VDA 2006) program committee.
- Served on *International Workshop on Volume Graphics 2005* program committee.
- Served on *Conference on Visual Data Exploration and Analysis 2005* (VDA 2005) program committee.
- Served as *session chair*, “Studies III: Interaction and Collaboration”, IEEE Virtual Reality 2005, Bonn, Germany, March 16, 2005.
- Served on *IEEE Virtual Reality 2005* International Program Committee, Bonn, Germany, March 12–16, 2005.

<u>Tenure Package Reviewing</u>

- University of North Carolina at Charlotte, Fall 2010.
- University of Louisiana at Lafayette, Fall 2008.

3. University service (committees, administrative accomplishments, etc.):

- *Human Subjects Institutional Review Board* (IRB) (standing), Alternate Member, 2010–2013.
- Chair of the *Five Year Program Review for the Department of Psychology* (ad-hoc), convened for the Office of the Provost, 2010.
- *Steering Committee* (standing), Institute for Neurocognitive Science and Technology (INST), 2007–2009.
- *Strategic Planning Committee* (standing), Department of Computer Science & Engineering, 2009–2010.
- *Faculty Search Committee* (ad-hoc), Department of Computer Science and Engineering, 2008–2009.

- *Undergraduate Student Recruitment Committee* (standing), Department of Computer Science and Engineering, 2008–2009.
- *Courses and Curricula Committee* (standing), Department of Computer Science and Engineering, 2005–2010.
- *Rotation For Theory Courses Committee* (ad-hoc), Department of Computer Science and Engineering, 2008–2009.
- *PhD Qualifying Exam Study Committee* (ad hoc), Department of Computer Science and Engineering, 2008.
- *Web Design Committee* (ad hoc), Department of Computer Science and Engineering, 2007–2008.
- *Senior Capstone Experience for Computer Science Majors* (ad hoc), Department of Computer Science and Engineering, 2007.
- *Graduate Studies Committee* (standing), Department of Computer Science and Engineering, 2006–2007.
- *Facilities Committee* (standing), Department of Computer Science and Engineering, 2004–2008.
- *Seminar Committee* (ad hoc), Department of Computer Science and Engineering, 2004.
- Wrote and graded *PhD Qualifying Exam Questions* for the Computer Science and Engineering PhD Program and the Computational Science PhD program, 2006–2010.
- Organized session for the CSE faculty retreat, Friday Oct 8, 2004. Held discussions with Ray Vaughn and Ed Allen, lead a discussion topic on "Increasing Funding Opportunities".

4. Other (academic advisement may be described here or as teaching):

Undergraduate Advising

- To date I have advised the following undergraduates, 2005–2010:
  1. Jonathan Hood
  2. Quantavious Montgomery (withdrew Fall 2009)
  3. Skylar Glass
  4. Neal Gompa
  5. David Martin
  6. Joseph Rollins
  7. Stephen Hill (changed to History Spring 2010)
  8. Nathan Hilton
  9. Matthew Hogan (graduated Spring 2007)
  10. Timothy Jordan (last semester Spring 2008)
  11. Juan Ferrer-Maldonado (graduated Fall 2008)
  12. Daniel Payment (graduated Spring 2007)
  13. Bryan Robbins (graduated Fall 2006)
  14. Stephen Rudolph (graduated Fall 2005)
  15. Blake Wall (graduated Fall 2008)
  16. Tinisha Walton (graduated Summer 2008 (College of Education))
  17. Adam Wandler (graduated Spring 2007)
  18. Nicholas Wells (graduated Spring 2007)
  19. Benjamin Williams (graduated Fall 2006)

Musical Service to the University

Unless otherwise noted, all listed service involves ensemble music performed upon bass guitar and vocals.

- *Summer Scholars On Stage 2010*, Division of Academic Outreach and Continuing Education, July 18–24, 2010. Arranged music and played bass guitar in stage band.
- *Center for Autonomic Computing Bi-Annual Meeting Dinner* at the Hotel Chester, High Performance Computing Collaboratory, October 29th, 2009. Organized the After 5 Jazz Band, arranged music, sang and played bass guitar.
- *Latin American Night*, Program by the Hispanic Student Association, October 27th, 2009. Worked with Dr. Robert J. Damm (professor of music), assisted with musical arrangements, rehearsed with and taught the music to the students, and played bass guitar on nine songs.

- *Summer Scholars On Stage 2009*, Division of Academic Outreach and Continuing Education, July 19–25, 2008. Arranged music and played bass guitar in stage band.
- *African Night 2009, A Musical Safari to Africa*, Program by the African Student Association, February 22nd, 2009. Worked with Dr. Robert J. Damm (professor of music), assisted with musical arrangements, rehearsed with and taught the music to the students, served as sound engineer, provided the PA, and played bass guitar on nine songs.
- *Summer Scholars 2008*, Division of Academic Outreach and Continuing Education, July 19–26, 2008. Arranged music and played bass guitar in stage band.
- *Staff Appreciation Day 2008*, Professional and Support Staff Advisory Council, May 9, 2008, organized Jukin' at the Junction band, sang and played guitar and bass guitar.
- *Celebrating African Night 2008*, presented by the African Students Association, February 24th, 2008, musical performance (bass guitar) on one song.
- *Faculty Recital*, Ms. Sheri Falcone, September 20th, 2007, musical performance (bass guitar) on three songs.
- *Student Recital*, Ms. Liz Tullos, April 22nd, 2007, musical performance (bass guitar) and teaching on two songs.
- *Faculty Recital*, Dr. Robert Damm, November 19th, 2006, musical performance (bass guitar) on one song.
- *Faculty Recital*, Ms. Sheri Falcone, September 27th, 2006, musical performance (bass guitar) on three songs.
- *Faculty Recital*, Dr. Jason Baker, August 27th, 2006, musical performance (bass guitar) on three songs.
- *Graduate Student Association* annual officer introduction event, April 28th, 2006, musical performance with the *Mississippi Jazz Alliance*.
- *Faculty Recital*, Dr. Richard Human, April 6th, 2006, played bass on two songs, arranged one song.
- *MSU International Fiesta*, April 1st, 2006, played bass and sang on three songs with the *Choral Relief Band* (arranged by Dr. Joe Ray Underwood).
- *President Lee's University Christmas Party*, December 9th, 2005, musical performance with the *Choral Relief Band* (arranged by Dr. Joe Ray Underwood).
- *Faculty Recital*, Ms. Sheri Falcone, September 29th, 2005, played bass on three songs.
- *Department of Counseling Education annual departmental crawfish boil*, April 23rd, 2005, musical performance with the *Choral Relief Band* (arranged by Dr. Joe Ray Underwood).

III. Awards and distinctions (title, date, organization):

- Inducted into the **Bagley College of Engineering Academy of Distinguished Teachers**, March 11, 2009
- **Bagley College of Engineering Outstanding Research Paper Award**, Spring 2008, Mississippi State University, for the publication "*Egocentric Depth Judgments in Optical, See-Through Augmented Reality*"
- Elected to **Upsilon Pi Epsilon**, April 18th, 2006, Mississippi State University
- **Honorable Mention Award**, March 29th, 2006, IEEE Virtual Reality 2006, for the publication "*A Perceptual Matching Technique for Depth Judgments in Optical, See-Through Augmented Reality*"

IV. Memberships in learned and professional societies. Society, dates of membership, offices held:

- IEEE, IEEE Computer Society, 1994–present. I have held numerous conference offices, which are described above and (for those held before employment at MSU) on my vita.
- IEEE Computer Society Technical Committee on Visualization and Graphics: 1995–present.
- Association for Computing Machinery, SIGGRAPH and SIGCHI, 1992–present.
- American Society for Engineering Education, 2004–present.

V. Previous academic ranks, institutions, dates:

None

VI. Non-academic positions held prior to appointment at MSU:

- Scientist, *The Naval Research Laboratory*, Washington, DC, 1997–2004.

J. Edward Swan II

Curriculum Vitae

Associate Professor, Department of Computer and Science and Engineering
Adjunct Associate Professor, Department of Psychology
Mississippi State University

Contact Information

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300 Butler Hall
Mississippi State University, MS 39762, USA.

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Email: swan@acm.org

Interests and Expertise

- Augmented and Virtual Reality
- Scientific and Information Visualization
- Perceptual and Cognitive Evaluation Techniques
- Empirical Methods (Experimental Design, Statistical Analysis)
- Human-Computer Interaction
- Computer Graphics
- Theoretical Computer Science

Education

1997 **Ph.D. in Computer Science**, The Ohio State University, Columbus, Ohio.
Concentration: computer and volume graphics. *Dissertation Title*: Object-Order Rendering of Discrete Objects. *Advisor*: Roni Yagel. *Defense Date*: May 12, 1997.

1992 **M.S. in Computer Science**, The Ohio State University, Columbus, Ohio.
Concentration: human-computer interaction. *Advisor*: Gary Perlman.

1989 **B.S. in Computer Science**, Auburn University, Auburn, Alabama.
Minor concentration: statistics, graph theory, digital coding theory.

Appointments

2007 – Present **Adjunct Associate Professor**, Psychology, Mississippi State University, MS.

2004 – Present **Associate Professor**, Computer Science and Engineering, Mississippi State University, MS.

1997 – 2004 **Scientist**, The Naval Research Laboratory, Washington, DC.
Affiliated with the Virtual Reality Laboratory.

1990 – 1997 **Graduate Research and Teaching Assistant**, Ohio State University, Columbus, OH.
Affiliated with the Computer and Information Science Department (CIS) and the Advanced Computing Center for the Arts and Design (ACCAD)

J. Edward Swan II

Honors and Awards

2009 Inducted into the **Bagley College of Engineering Academy of Distinguished Teachers**, March 11, 2009

2008 **Bagley College of Engineering Outstanding Research Paper Award**, for the publication "*Egocentric Depth Judgments in Optical, See-Through Augmented Reality*", Spring 2008

2006 **Honorable Mention Award**, IEEE Virtual Reality 2006, for the publication "*A Perceptual Matching Technique for Depth Judgments in Optical, See-Through Augmented Reality*".

2006 Elected to **Upsilon Pi Epsilon** (Honor Society in the Computing Sciences), Mississippi State University.

2004 **Alan Berman Publication Award**, The Naval Research Laboratory, for the publication "*Resolving Multiple Occluded Layers in Augmented Reality*".

1999 **Best Paper Award**, IEEE Virtual Reality 1999, for the publication "*User-Centered Design and Evaluation of a Real-Time Battlefield Visualization Virtual Environment*".

1998 **Naval Notable Achievement Award**, The Naval Research Laboratory, for the publication "*Splatting Errors and Antialiasing*".

1997 **Best Paper Award**, IEEE Visualization 1997, for the publication "*An Anti-Aliasing Technique for Splatting*".

1989 B.S. received **Magna Cum Laude**; elected to **Phi Kappa Phi**, Auburn University.

1987 Elected to **Upsilon Pi Epsilon** (Honor Society in the Computing Sciences), Auburn University.

1985 Elected to **Phi Eta Sigma** (Freshman Honor Society), Auburn University.

Grants

At Mississippi State University

To date at Mississippi State University, Dr. Swan has been PI or Co-PI on 11 grants totaling $1.94M.

1. **J. Edward Swan II** (Principal Investigator), "HCC: Small: Depth Perception in Near- and Medium-Field Augmented Reality" (IIS-1018413), The *National Science Foundation* (NSF), Information and Intelligent Systems (IIS), Human-Centered Computing (HCC), $499,998; October 1, 2010 to September 30, 2013.

2. **J. Edward Swan II** (Principal Investigator), "Depth Perception in Near-Field Augmented Reality", *The Mississippi Space Grant Consortium, National Aeronautics and Space Administration* (NASA). $49,138; January 10, 2010 to January 9, 2011.

3. T.J. Jankun-Kelly, **J. Edward Swan II** (Principal Instigators), "Game Technology for Increasing Interest in Computer Science", 2008 Schilling Special Teaching Project Proposal, *Mississippi State University*, $2,833; July 1, 2008 to June 30, 2009.

4. **J. Edward Swan II** (Principal Investigator), "HCC: Egocentric Depth Perception in Augmented Reality" (IIS-0713609), The *National Science Foundation* (NSF), Information and Intelligent Systems (IIS), Human-Centered Computing (HCC), $392,268; October 1, 2007 to September 30, 2010.

5. Robert J. Moorhead, **J. Edward Swan II** (Principal Investigators), "High Performance Computing Visualization Initiative: Visualization User Studies", *Department of the Army* (DoD) (subcontract; Jackson State University prime contractor), $149,944; August 15, 2005 to June 30, 2007.

6. T.J. Jankun-Kelly, Jeff Carver, Dave Dampier, **J. Edward Swan II** (Principal Investigators), "CT-ISG: Empirically-Based Visualization for Computer Security and Forensics" (CNS-0627407), The *National Science Foundation* (NSF) CNS CyberTrust. $300,000; October 1, 2006 to September 30, 2009.

7. **J. Edward Swan II**, Stephen R. Ellis (Principal Investigators), "Vibration-Stabilizing Information Displays during Launch with Augmented Reality Technology" (NNG05GJ72H), *The Mississippi Space Grant Consortium, National Aeronautics and Space Administration* (NASA). $42,846; April 1, 2006 to March 31, 2007.

8. Jeff Carver, **J. Edward Swan II** (Principal Investigators), "Time-Domain Visualization of Software Source Code and Lifecycle Documents", *The Center for Computer Security Research* (CCSR), *Mississippi State University*. $20,000; January 1, 2006 to August 31, 2006.

9. **J. Edward Swan II** (Principal Investigator), "Depth Perception in Augmented Reality", 2006 Research Initiation Program, *The Office of Research*, *Mississippi State University*. $10,000; January 1, 2006 to December 31, 2006.

10. T.J. Jankun-Kelly, **J. Edward Swan II** (Principal Investigators), "Acquisition of a Display Wall for Human Systems Research and Biological Imaging", The *National Science Foundation* (NSF), CNS0521564 05080745. $425,487; August 1, 2005 to July 31, 2008.

11. **J. Edward Swan II** (Principal Investigator), "Building An Infrastructure for Augmented Reality Perceptual Research and Engineering at the INST", The *Office of Naval Research* (ONR), a seed grant through the *Institute for Neurocognitive Science and Technology* (INST) under the ONR grant "Optimizing Adaptive Warrior Performance", MSU 006252-005 (subcontract of ONR N000140410341). $52,757; January 2005 to May 2006.

At the Naval Research Laboratory

In 7 years at the Naval Research Laboratory, Dr. Swan was PI or Co-PI on 10 grants totaling $6.49M. These grants supported a total of 30.9 person-years of effort, which averages 4.4 person-years per year.

12. **J. Edward Swan II**, Harvey Smallman (Principal Investigators), "Occlusion and Depth Perception in Augmented Reality: Making 'X-Ray Vision' Work." The *Naval Research Laboratory, Advanced Information Technology* (AIT) research funding. $100,000; FY 2004.

13. **J. Edward Swan II**, Phil Cohen (Principal Investigators), "Interoperable Multi-Modal Interaction and Display System (IMMIDS)." The *Office of Naval Research* 6.2 Discovery and Invention Command and Control and Combat Systems Program (ONR 311). $1,275,000; FY 2002–04.

14. Gregory S. Schmidt, **J. Edward Swan II** (Principal Investigators), "Visualization of Battlefield Uncertainty (VBU)." The *Office of Naval Research* 6.2 Discovery and Invention Command and Control and Combat Systems Program (ONR 311). $500,000; FY 2002–03.

15. Roger Hillson, **J. Edward Swan II** (Principal Investigators), "Human Performance in Virtual Environments During Simulated Shipboard Motion." The *Office of Naval Research* 6.2 Human Systems, Medical Science and Technology Program (ONR 341). $300,000; FY 2001–02.

16. **J. Edward Swan II** (Principal Investigator), "Exploring Multimodal 3D Interfaces." The *Office of Naval Research* 6.1. $1,000,000; FY 1999–2002.

17. Simon J. Julier, **J. Edward Swan II** (Principal Investigators), "Battlefield Augmented Reality System (BARS)." The *Office of Naval Research* 6.2 Discovery and Invention Command and Control and Combat Systems Program. $1,375,000; FY 1999–2001.

18. **J. Edward Swan II** (Principal Investigator), "Interoperable Virtual Reality System (IVRS)." The *Office of Naval Research* 6.2 Discovery and Invention Command and Control and Combat Systems Program. $1,215,000; FY 1999–2001.

19. **J. Edward Swan II** (Principal Investigator), "Volume Graphics Approaches to Battlefield Visualization". The *Office of Naval Research* 6.1. $300,000; FY 1998–2000.

20. **J. Edward Swan II** (Principal Investigator), "Technical Advice to RAIVE Project", The *Office of Naval Research*. $25,000; FY 1998.

21. James Durbin, Lawrence J. Rosenblum, **J. Edward Swan II**, David Tate (Principal Investigators), "Human-Centered Computing." The *Office of Naval Research* 6.2 Command and Control and Combat Systems Program. $400,000; FY 1998.

J. Edward Swan II

Publications

Italicized names are student co-authors.

Award-Winning Publications (all refereed)

- **J. Edward Swan II**, *Adam Jones*, *Eric Kolstad*, Mark A. Livingston, Harvey S. Smallman, “Egocentric Depth Judgments in Optical, See-Through Augmented Reality”, *IEEE Transactions on Visualization and Computer Graphics*, Volume 13, Number 3, May/June 2007, pages 429–442. **Winner of the 2008 Bagley College of Engineering Outstanding Research Paper Award**.
- **J. Edward Swan II**, Mark A. Livingston, Harvey S. Smallman, Dennis Brown, Yohan Baillot, Joseph L. Gabbard, Deborah Hix, “A Perceptual Matching Technique for Depth Judgments in Optical, See-Through Augmented Reality”, *Technical Papers*, *Proceedings of IEEE Virtual Reality 2006*, Alexandria, Virginia, USA, March 25–29, IEEE Computer Society, pages 19–26. Acceptance rate: 28% (27 out of 95). **Winner of an “Honorable Mention” award at IEEE Virtual Reality 2006.** Award rate: 11% (3 out of 27).
- Mark A. Livingston, **J. Edward Swan II**, Joseph L. Gabbard, *Tobias H. Höllerer*, Deborah Hix, Simon J. Julier, Yohan Baillot, Dennis Brown, “Resolving Multiple Occluded Layers in Augmented Reality”, *Technical Papers*, *The 2nd International Symposium on Mixed and Augmented Reality* (ISMAR ’03), Tokyo, Japan, October 7–10, 2003, IEEE Computer Society, pages 56–65. Acceptance rate: 33% (25 out of 75). **Winner of a 2004 NRL Alan Berman Publication Award**. Award rate: 3% (35 such awards were given, out of 1106 NRL publications).
- Deborah Hix, **J. Edward Swan II**, Joseph L. Gabbard, *Mike McGee*, Jim Durbin, Tony King, “User-Centered Design and Evaluation of a Real-Time Battlefield Visualization Virtual Environment”, *Proceedings of IEEE Virtual Reality ‘99*, Houston, Texas, USA, March 13–17, 1999, IEEE Computer Society Press, pages 96–103. Acceptance rate: 33% (33 out of 100). **Winner of the “Best Paper” award at IEEE Virtual Reality ‘99**. Award rate: 3% (1 out of 33).
- Klaus Mueller, Torsten Möller, **J. Edward Swan II**, Roger Crawfis, Naeem Shareef, Roni Yagel, “Splatting Errors and Antialiasing”. *IEEE Transactions on Visualization and Computer Graphics*, Volume 4, Number 2, IEEE Computer Society: April–June 1998, pages 178–191. **Winner of a Naval “Notable Achievement” Award**.
- **J. Edward Swan II**, Klaus Mueller, Torsten Möller, Naeem Shareef, Roger Crawfis, Roni Yagel, “An Anti-Aliasing Technique for Splatting”. *Proceedings of IEEE Visualization ‘97*, Phoenix, Arizona, USA, October 19–24, 1997, IEEE Computer Society Press, pages 197–204. Acceptance rate: 26% (44 out of 170). **Winner of the “Best Paper” award at IEEE Visualization ‘97**. Award rate: 2% (1 out of 50).

Refereed Journal Publications

1. T.J. Jankun-Kelly, *Yagneshwara Somayajulu Lanka*, **J. Edward Swan II**, “An Evaluation of Glyph Perception for Real Symmetric Traceless Tensor Properties”, *Computer Graphics Forum: The International Journal of the Eurographics Association*, (Special Issue on EuroVis 2010), June 2010, Volume 29, Number 3, pages 1133–1142.
2. T.J. Jankun-Kelly, *David Wilson*, *Andrew S. Stamps*, *Josh Franck*, Jeffry Carver, **J. Edward Swan II**, “Visual Analysis for Textual Relationships in Digital Forensics Evidence”, *Information Visualization*, Special Issue on VizSec 2009, *in press*.
3. *Chad A Steed*, Patrick J. Fitzpatrick, **J. Edward Swan II**, T.J. Jankun-Kelly, “Tropical Cyclone Trend Analysis using Enhanced Parallel Coordinates and Statistical Analysis”, *Cartography and Geographic Information Science*, July 2009, Volume 36, Issue 3, pages 251–265.
4. *Chad A. Steed*, Patrick J. Fitzpatrick, T.J. Jankun-Kelly, *Amber Yancey*, **J. Edward Swan II**, “An Interactive Parallel Coordinates Technique Applied to a Tropical Cyclone Climate Analysis”, *Computers & Geosciences*, July 2009, Volume 35, Issue 7, pages 1529–1539.

5. *Joseph L. Gabbard*, **J. Edward Swan II**, “Usability Engineering for Augmented Reality: Employing User-based Studies to Inform Design”, *IEEE Transactions on Visualization and Computer Graphics*, May/June 2008, Volume 14, Number 3, pages 513–525.

6. *Joel P. Martin*, **J. Edward Swan II**, Robert J. Moorhead II, Zhanping Liu, *Shangshu Cai*, “Results of a User Study on 2D Hurricane Visualization”, *Computer Graphics Forum: The International Journal of the Eurographics Association (Special Issue of EuroVis 2008)*, May 2008, Volume 27, Number 3, Pages 991–998.

7. **J. Edward Swan II**, *Adam Jones*, *Eric Kolstad*, Mark A. Livingston, Harvey S. Smallman, “Egocentric Depth Judgments in Optical, See-Through Augmented Reality”, *IEEE Transactions on Visualization and Computer Graphics*, Volume 13, Number 3, May/June 2007, pages 429–442. **Winner of the 2008 Bagley College of Engineering Outstanding Research Paper Award**.

8. Greg Schmidt, Dennis G. Brown, *Erik B. Tomlin*, **J. Edward Swan II**, Yohan Baillot, “Probabilistic Algorithms, Integration, and Empirical Evaluation for Disambiguating Multiple Selections in Frustum-Based Pointing”, *Journal of Multimedia*, Volume 1, Issue 3, June 2006, pages 1–12.

9. *Joseph L. Gabbard*, **J. Edward Swan II**, Deborah Hix, “The Effects of Text Drawing Styles, Background Textures, and Natural Lighting on Text Legibility in Outdoor Augmented Reality”, *PRESENCE: Teleoperators and Virtual Environments*, Volume 15, Number 1, February 2006, pages 16–32.

10. *Joseph L. Gabbard*, Deborah Hix, **J. Edward Swan II**, “User-Centered Design and Evaluation of Virtual Environments”, *IEEE Computer Graphics and Applications*, Volume 19, Number 6, November / December, 1999, pages 51–59.

11. Klaus Mueller, Torsten Möller, **J. Edward Swan II**, Roger Crawfis, Naeem Shareef, Roni Yagel, “Splatting Errors and Antialiasing”. *IEEE Transactions on Visualization and Computer Graphics*, Volume 4, Number 2, IEEE Computer Society: April–June 1998, pages 178–191. **Winner of a Naval “Notable Achievement” Award**.

12. Gregory J. Wiet, Don Stredney, Roni Yagel, **J. Edward Swan II**, Naeem Shareef, Petra Schmalbrock, K. Right, Jack Smith, and D. E. Schuller, “Cranial Base Tumor Visualization through High Performance Computing”, *Journal of Studies in Health Technology and Informatics: Health Care in the Information Age*, H. Sieburg, S. Weghorst, K. Morgan (Eds.), Volume 29, January 1996, pages 43–59.

13. Don Stredney, Wayne Carlson, **J. Edward Swan II**, Beth Blostein, “The Determination of Environmental Accessibility and ADA Compliance through Virtual Wheelchair Simulation”, *PRESENCE: Teleoperators and Virtual Environments*; First Special Issue on The Application of Virtual Environments to Architecture, Building, and Large Structure Design, Volume 4, Number 3, Summer 1995, MIT Press, pages 297–305.

Refereed Conference Publications[1]

14. Ernst Kruijff, **J. Edward Swan II**, Steve Feiner, “Perceptual Issues in Augmented Reality Revisited”, (to appear in) *Technical Papers*, *IEEE International Symposium on Mixed and Augmented Reality* (ISMAR 2010), Seoul, Korea, October 13–16, 2010, Acceptance rate: 22% (24 out of 107).

15. *Gurjot Singh*, **J. Edward Swan II**, *J. Adam Jones*, Stephen R. Ellis, “Depth Judgment Measures and Occluding Surfaces in Near-Field Augmented Reality”, *Proceedings of the Symposium on Applied Perception in Graphics and Visualization* (APGV 2010), Los Angeles, California, USA, July 23–24, 2010, pages 149–156, Acceptance rate: 56% (27 out of 48).

[1] In my professional community, these full-text refereed conference articles have very low acceptance rates, are widely read, and have a professional impact that is comparable to journal articles. The acceptance rate is listed for every article where it could be found. When I worked for the Naval Research Laboratory, refereed conference articles were more highly valued than journal articles, because the conference articles involved greater research community involvement.

16. Joseph L. Gabbard, *Jason Zedlitz*, **J. Edward Swan II**, Woodrow W. Winchester III, "More Than Meets the Eye: An Engineering Study to Empirically Examine the Blending of Real and Virtual Color Spaces", *Technical Papers, Proceedings of IEEE Virtual Reality 2010*, Waltham, Massachusetts, USA, March 20–24, pages 79–86, Acceptance rate: 19% (20 out of 105).

17. T.J. Jankun-Kelly, *David Wilson*, *Andrew S. Stamps*, *Josh Franck*, Jeffery Carver, **J. Edward Swan II**, "A Visual Analytic Framework for Exploring Relationships in Textual Contents of Digital Forensics Evidence", *Proceedings of Workshop on Visualization for Cyber Security* (VizSec 2009), Atlantic City, New Jersey, USA, October 11, 2009, pages 39–44, Acceptance rate: 43% (10 out of 23).

18. *Chad A. Steed*, **J. Edward Swan II**, T.J. Jankun-Kelly, Patrick J. Fitzpatrick, "Guided Analysis of Hurricane Trends Using Statistical Processes Integrated with Interactive Parallel Coordinates", Proceedings of the *IEEE Symposium on Visual Analytics Science and Technology* (VAST 2009), Atlantic City, New Jersey, USA, October 12–13, pages 19–26, Acceptance rate: 38% (26 out of 69).

19. *Eric Klein*, **J. Edward Swan II**, Gregory S. Schmidt, Mark A. Livingston, Oliver G. Staadt, "Measurement Protocols for Medium-Field Distance Perception in Large-Screen Immersive Displays", *Technical Papers, Proceedings of IEEE Virtual Reality 2009*, Lafayette, Louisiana, USA, March 14–18, pages 107–113, Acceptance rate: 28% (21 out of 76).

20. Mark A. Livingston, Zhuming Ai, **J. Edward Swan II**, Harvey S. Smallman, "Indoor vs. Outdoor Depth Perception for Mobile Augmented Reality", *Technical Papers, Proceedings of IEEE Virtual Reality 2009*, Lafayette, Louisiana, USA, March 14–18, pages 55–61, Acceptance rate: 28% (21 out of 76).

21. *J. Adam Jones*, **J. Edward Swan II**, *Gurjot Singh*, *Eric Kolstad*, Stephen R. Ellis, "The Effects of Virtual Reality, Augmented Reality, and Motion Parallax on Egocentric Depth Perception", *Proceedings of the Symposium on Applied Perception in Graphics and Visualization* (APGV 2008), Los Angeles, California, USA, August 9–10, 2008, pages 9–14. Acceptance rate: 55% (23 out of 42).

22. T.J. Jankun-Kelly, *Josh Franck*, *David Wilson*, Jeffrey Carver, David Dampier, **J. Edward Swan II**, "Show Me How You See: Lessons from Studying Computer Forensics Experts for Visualization", *Proceedings of the Fifth International Workshop on Visualization for Computer Security* (VizSEC 2008), Cambridge, Massachusetts, USA, September 15, 2008, pages 80–86. Acceptance Rate: 67% (18 out of 27).

23. *Joseph L. Gabbard*, **J. Edward Swan II**, Deborah Hix, *Si-Jung Kim*, *Greg Fitch*, "Active Text Drawing Styles for Outdoor Augmented Reality: A User-Based Study and Design Implications", *Technical Papers*, *Proceedings of IEEE Virtual Reality 2007*, Charlotte, North Carolina, USA, March 10–14, pages 35–42. Acceptance rate: 20% (26 out of 130).

24. **J. Edward Swan II**, Mark A. Livingston, Harvey S. Smallman, Dennis Brown, Yohan Baillot, *Joseph L. Gabbard*, Deborah Hix, "A Perceptual Matching Technique for Depth Judgments in Optical, See-Through Augmented Reality", *Technical Papers, Proceedings of IEEE Virtual Reality 2006*, Alexandria, Virginia, USA, March 25–29, IEEE Computer Society, pages 19–26. Acceptance rate: 28% (27 out of 95). **Winner of an "Honorable Mention" award at IEEE Virtual Reality 2006.** Award rate: 11% (3 out of 27).

25. Greg Schmidt, Dennis G. Brown, *Erik B. Tomlin*, **J. Edward Swan II**, Yohan Baillot, "Toward Disambiguating Multiple Selections for Frustum-Based Pointing", *Technical Papers*, *Proceedings of the 1st IEEE Symposium on 3D User Interfaces* (3DUI 2006), Alexandria, Virginia, USA, March 25–26, 2006, pages 87–94. Acceptance rate: 33% (18 out of 54).

26. *Joseph L. Gabbard*, **J. Edward Swan II**, Deborah Hix, Robert S. Schulman, *John Lucas*, *Divya Gupta*, "An Empirical User-Based Study of Text Drawing Styles and Outdoor Background Textures for Augmented Reality", *Technical Papers, Proceedings of IEEE Virtual Reality 2005*, Bonn, Germany, March 12–16, 2005, IEEE Computer Society, pages 11–18. Acceptance rate: 26% (29 out of 111).

27. Deborah Hix, *Joseph L. Gabbard*, **J. Edward Swan II**, Mark A. Livingston, Tobias H. Höllerer, Simon J. Julier, Yohan Baillot, Dennis Brown, “A Cost-Effective Usability Evaluation Progression for Novel Interactive Systems”, *Hawaii International Conference on System Sciences* (HICSS-37), Waikoloa, Hawaii, USA, January 5–8, 2004.

28. Mark A. Livingston, **J. Edward Swan II**, *Joseph L. Gabbard*, Tobias H. Höllerer, Deborah Hix, Simon J. Julier, Yohan Baillot, Dennis Brown, “Resolving Multiple Occluded Layers in Augmented Reality”, *Technical Papers*, *The IEEE / ACM International Symposium on Mixed and Augmented Reality* (ISMAR 2003), Tokyo, Japan, October 7–10, 2003, IEEE Computer Society, pages 56–65. Acceptance rate: 33% (25 out of 75). **Winner of a 2004 NRL Alan Berman Publication Award**. Award rate: 3% (35 such awards were given, out of 1106 NRL publications).

29. **J. Edward Swan II**, *Joseph L. Gabbard*, Deborah Hix, Robert S. Schulman, *Keun Pyo Kim*, “A Comparative Study of User Performance in a Map-Based Virtual Environment”, *Technical Papers*, *Proceedings of IEEE Virtual Reality 2003*, Los Angeles, California, USA, March 22–26, 2003, IEEE Computer Society, pages 259–266. Acceptance rate: 28% (29 out of 103).

30. **J. Edward Swan II**, Marco Lanzagorta, Doug Maxwell, Eddy Kuo, Jeff Uhlmann, Wendell Anderson, Haw-Jye Shyu, William Smith, “A Computational Steering System for Studying Microwave Interactions with Missile Bodies”, *Proceedings of IEEE Visualization 2000*, Salt Lake City, Utah, USA, October 8–13, 2000, IEEE Computer Society Press, pages 441–444. Acceptance rate: 34% (52 out of 151).

31. *Baoquan Chen*, **J. Edward Swan II**, Eddy Kuo, Arie Kaufman, “LOD-Sprite Technique for Accelerated Terrain Rendering”, *Proceedings of IEEE Visualization ‘99*, San Francisco, California, USA, October 24–29, 1999, IEEE Computer Society Press, pages 291–298. Acceptance rate: 36% (47 out of 129).

32. Deborah Hix, **J. Edward Swan II**, Joseph L. Gabbard, Mike McGee, Jim Durbin, Tony King, “User-Centered Design and Evaluation of a Real-Time Battlefield Visualization Virtual Environment”, *Proceedings of IEEE Virtual Reality ‘99*, Houston, Texas, USA, March 13–17, 1999, IEEE Computer Society Press, pages 96–103. Acceptance rate: 30% (33 out of 100). **Winner of the “Best Paper” award at IEEE Virtual Reality ‘99**. Award rate: 3% (1 out of 33).

33. Jim Durbin, **J. Edward Swan II**, Brad Colbert, John Crowe, Rob King, Tony King, Chris Scannell, Zachary Wartell, Terry Welsh, “Battlefield Visualization on the Responsive Workbench”, *Case Studies*, *Proceedings of IEEE Visualization ‘98*, Research Triangle Park, North Carolina, USA, October 18–23, 1998, IEEE Computer Society Press, pages 463–466. Acceptance rate: 67% (22 out of 33).

34. Marco Lanzagorta, Milo V. Kral, **J. Edward Swan II**, George Spanos, Rob Rosenberg, Eddy Kuo, “Three-Dimensional Visualization of Microstructures”, *Case Studies*, *Proceedings of IEEE Visualization ‘98*, Research Triangle Park, North Carolina, USA, October 18–23, 1998, IEEE Computer Society Press, pages 487–490. Acceptance rate: 67% (22 out of 33).

35. **J. Edward Swan II**, Klaus Mueller, Torsten Möller, Naeem Shareef, Roger Crawfis, Roni Yagel, “An Anti-Aliasing Technique for Splatting”. *Proceedings of IEEE Visualization ‘97*, Phoenix, Arizona, USA, October 19–24, 1997, IEEE Computer Society Press, pages 197–204. Acceptance rate: 26% (44 out of 170). **Winner of the “Best Paper” award at IEEE Visualization ‘97**. Award rate: 2% (1 out of 50).

36. Raghu Machiraju, **Edward Swan**, Roni Yagel, “Spatial Domain Characterization and Control of Reconstruction Errors”. *Proceedings of the 6th EuroGraphics Rendering Workshop ‘95*, Dublin, Ireland, June 12–14, 1995, pages 33–44.

37. Gary Perlman, **J. Edward Swan II**, “Relative Effects of Color-, Texture-, and Density-Coding on Visual Search Performance and Subjective Preference”, *Proceedings of the 38th Annual Meeting of the Human Factors and Ergonomics Society*, Nashville, Tennessee, USA, October 24–28, 1994, HFES, pages 235–239.

38. Gary Perlman, **J. Edward Swan II**, "Color versus Texture Coding to Improve Visual Search Performance", *Proceedings of the 37th Annual Meeting of the Human Factors and Ergonomics Society*, Santa Monica, California, USA, HFES, October 11–15, 1993, pages 343–347. Also appears in G. Perlman, G. K. Green, & M. S. Wogalter (Eds.), *Human Factors Perspectives on Human-Computer Interaction: Selections from the Human Factors and Ergonomics Society Annual Meetings 1983–1994*, Santa Monica, California, HFES, 1995.

Refereed Abstracts

39. Chad A. Steed, T.J. Jankun-Kelly, **J. Edward Swan II**, Robert J. Moorhead, "Illustrative Visualization of Hurricane Advisory Information", *Poster Compendium*, *Proceedings of IEEE Visualization 2009*, Atlantic City, New Jersey, USA, October 11–16, 2009.

40. *Chad A. Steed*, Patrick J. Fitzpatrick, T.J. Jankun-Kelly, **J. Edward Swan II**, "North Atlantic Hurricane Trend Analysis using Parallel Coordinates and Statistical Techniques", Workshop on Geo-Spatial Visual Analytics 2008, *Fifth International Conference on Geographic Information Science*, September 23–26, Park City, Utah, USA.

41. *Adam Jones*, **J. Edward Swan II**, *Gurjot Singh*, *Eric Kolstad*, "The Effects of Virtual Reality, Augmented Reality, and Motion Parallax on Egocentric Depth Perception", *Poster Compendium*, *Proceedings of IEEE Virtual Reality 2008*, Reno, Nevada, USA, March 8–12, 2008, pages 267–268.

42. *Chad Steed*, Patrick Fitzpatrick, T.J. Jankun-Kelly, *Amber Yancey*, **J. Edward Swan II**, "Practical Applications of Parallel Coordinates to Hurricane Trend Analysis", *Poster Compendium*, *Proceedings of IEEE Visualization 2007*, Sacramento, California, USA, October 28 – November 1, 2007.

43. Mark A. Livingston, *Catherine Zanbaka*, **J. Edward Swan II**, Harvey S. Smallman, "Objective Measures for the Effectiveness of Augmented Reality", *Poster Compendium*, *Proceedings of IEEE Virtual Reality 2005*, Bonn, Germany, March 12–16, 2005, IEEE Computer Society, pages 287–288.

44. Yohan Baillot, *Joshua J. Eliason*, Greg S. Schmidt, **J. Edward Swan II**, Dennis Brown, Simon Julier, Mark A. Livingston, Lawrence Rosenblum, "Evaluation of the ShapeTape Tracker for Wearable, Mobile Interaction", *Poster Papers*, *Proceedings of IEEE Virtual Reality 2003*, Los Angeles, California, USA, March 22–26, 2003, IEEE Computer Society, pages 285–286.

Workshop or Position Papers

45. Chad A. Steed, T.J. Jankun-Kelly, **J. Edward Swan II**, Robert J. Moorhead, "Illustrative Visualization Techniques for Hurricane Advisory Information", *Proceedings of the Oceans '09 MTS/IEEE Biloxi Technical Program*, October 26–29, 2009, Biloxi, MS, USA.

46. **J. Edward Swan II**, *Joseph L. Gabbard*, "Survey of User-Based Experimentation in Augmented Reality", *Proceedings of 1st International Conference on Virtual Reality*, *HCI International 2005*, Las Vegas, Nevada, USA, July 22–27, 2005.

47. Mark A. Livingston, Dennis Brown, **J. Edward Swan II**, Brian Goldiez, Yohan Baillot, Simon J. Julier, Greg S. Schmidt, "Applying a Testing Methodology for Augmented Reality Interfaces to Simulation Systems", *2005 International Conference on Human-Computer Interface Advances for Modeling and Simulation* (SIMCHI '05), New Orleans, Louisiana, USA, January 23–25, 2005.

48. Mark A. Livingston, **J. Edward Swan II**, Simon J. Julier, Yohan Baillot, Dennis Brown, Lawrence J. Rosenblum, *Joseph L. Gabbard*, Tobias H. Höllerer, Deborah Hix, "Evaluating System Capabilities and User Performance in the Battlefield Augmented Reality System", *Performance Metrics for Intelligent Systems Workshop* (PerMIS '04), Gaithersburg, Maryland, USA, August 24–26, 2004.

49. Simon Julier, Mark A. Livingston, **J. Edward Swan II**, Yohan Baillot, Dennis Brown, "Adaptive User Interfaces in Augmented Reality", Workshop on Software Technology for Augmented Reality Systems (STARS), *The 2nd International Symposium on Mixed and Augmented Reality* (ISMAR '03), Tokyo, Japan, October 7–10, 2003.

50. *Joseph L. Gabbard*, Deborah Hix, **J. Edward Swan II**, Mark A. Livingston, Tobias H. Höllerer, Simon J. Julier, Dennis Brown, Yohan Baillot, "Usability Engineering for Complex Interactive Systems Development", *Engineering for Usability, Human Systems Integration Symposium 2003*, Vienna, Virginia, USA, June 23–25, 2003.

51. **J. Edward Swan II**, "Far-Field Occlusion and Distance Perception in Augmented Reality", *Office of Naval Research Workshop on Attention, Perception, and Modeling for Complex Displays*, Troy, New York, USA, June 4–6, 2003.

52. Mark A. Livingston, Lawrence J. Rosenblum, Simon J. Julier, Dennis Brown, Yohan Baillot, **J. Edward Swan II**, *Joseph L. Gabbard*, Deborah Hix, "An Augmented Reality System for Military Operations in Urban Terrain", *Proceedings of the Interservice / Industry Training, Simulation, & Education Conference* (I/ITSEC '02), Orlando, Florida, USA, December 2–5, 2002.

53. Douglas B. Maxwell, *Aaron Bryden*, Greg S. Schmidt, *Ian Roth*, **J. Edward Swan II**, "Integration of a Commodity Cluster into an Existing 4-Wall Display System", Workshop on Commodity-Based Visualization Clusters, *Proceedings of IEEE Visualization 2002*, Boston, Massachusetts, USA, October 27, 2002.

54. *Joseph L. Gabbard*, **J. Edward Swan II**, Deborah Hix, Marco Lanzagorta, Mark Livingston, Dennis Brown, Simon Julier, "Usability Engineering: Domain Analysis Activities for Augmented Reality Systems", *The Engineering Reality of Virtual Reality 2002*, A. Woods, J. Merritt, S. Benton, M. Bolas, Editors, *Proceedings of SPIE Volume 4660, Stereoscopic Displays and Virtual Reality Systems IX*, January 2002, pages 445–457.

55. **J. Edward Swan II**, *Jesus Arango, Bala Nakshatrala*, "Interactive, Distributed, Hardware-Accelerated LOD-Sprite Terrain Rendering with Stable Frame Rates", *Visualization and Data Analysis 2002*, R. Erbacher, P. Chen, M. Gröhn, J. Roberts, C. Wittenbrink, Editors, *Proceedings of SPIE Volume 4665*, January 2002, pages 177–188.

56. Shu-Chieh Wu, Jack W. Smith, **J. Edward Swan II**, "Pilot Study on the Effects of a Computer-Based Medical Image System". Proceedings of the *Seventeenth Annual Fall Symposium of the American Medical Informatics Association* (AMIA), Washington, DC, USA, October 26–30, 1996, New York: Hanley & Belfus, Inc., pages 674–678.

57. Roni Yagel, Don Stredney, Gregory J. Wiet, Petra Schmalbrock, Dennis J. Sessanna, Yair Kurzion, **Edward Swan**, Naeem Shareef, Jack Smith, and D.E. Schuller, "Cranial Base Tumor Visualization through Multimodal Imaging Integration and Interactive Display," *Proceedings of the Fourth Meeting of the International Society of Magnetic Resonance in Medicine*, New York, New York, USA, April 29, 1996.

58. Wayne Carlson, **J. Edward Swan II**, Don Stredney, Beth Blostein, "The Application of Virtual Wheelchair Simulation to the Determination of Environmental Accessibility and Standards Compliance in Architectural Design", *Proceedings of the Symposium on Computers & Innovative Architectural Design, The 7th International Conference on Systems Research, Informatics & Cybernetics* (ICSRIC '94), J.W. Brahan, Ed., Baden-Baden, Germany, August 18, 1994.

59. **J. Edward Swan II**, Don Stredney, Wayne Carlson, Beth Blostein, "The Determination of Wheelchair User Proficiency and Environmental Accessibility Through Virtual Simulation", *Proceedings of the Second Annual International Conference: "Virtual Reality and Persons with Disabilities"*, California State University, Northridge, California, Center on Disabilities, June 9–10, 1994, pages 156–161.

Other Publications

60. *Gurjot Singh*, **J. Edward Swan II**, *J. Adam Jones*, *Lorraine Lin*, Stephen R. Ellis, "Depth Judgment Measures and Occluders in Near-Field Augmented Reality", *Poster Compendium, Proceedings of Symposium on Applied Perception in Graphics and Visualization* (APGV 2009), Chania, Crete, Greece, September 30–October 2, 2009, page 127.

61. *J. Adam Jones*, **J. Edward Swan II**, *Gurjot Singh*, *Josh Franck*, Stephen R. Ellis, "The Effects of Continued Exposure to Medium Field Augmented and Virtual Reality on the Perception of Egocentric Depth", *Poster Compendium, Proceedings of Symposium on Applied Perception in Graphics and Visualization* (APGV 2009), Chania, Crete, Greece, September 30–October 2, 2009, page 138.

62. Joseph J. LaViola Jr., Doug A. Bowman, Stephen R. Ellis, Victoria Interrante, Benjamin C. Lok, **J. Edward Swan II**, "User Studies in VR: What Can We Learn From Them and What Are They Good For?", *Panels, Proceedings of IEEE Virtual Reality 2008*, Reno, Nevada, USA, March 8–12, 2008, pages 303–304.

63. Victoria Interrante, Joseph K. Kearney, Dennis Proffitt, **J. Edward Swan II**, William B. Thompson, "Spatial Perception in Immersive Virtual Environments: New Theories and Current Controversies", *Panels*, *Proceedings of IEEE Virtual Reality 2007*, Charlotte, North Carolina, USA, March 10–14, 2007, pages 315–316.

64. *Eric Klein*, Oliver Staadt, **J. Edward Swan II**, Greg Schmidt, Mark Livingston, "Egocentric Medium-Field Distance Perception in Projection Environments", *Poster Compendium, Proceedings of Symposium on Applied Perception in Graphics and Visualization* (APGV 2006), Boston, Massachusetts, USA, July 28–29, 2006, page 147.

65. S. Augustine Su, Robert King, **J. Edward Swan II**, Lawrence Rosenblum, "Exploring Multimodal 3D Interfaces", Proceedings of the Workshop on Perceptual and Multi-Modal Interfaces, *IEEE Virtual Reality 2000*, New Brunswick, New Jersey, USA, March 19, 2000.

66. **J. Edward Swan II**, Theresa-Marie Rhyne, David Laidlaw, Tamara Munzner, Victoria Interrante, "Visualization Needs More Visual Design!", *Panels, Proceedings of IEEE Visualization '99*, San Francisco, California, USA, October 24–29, 1999, IEEE Computer Society Press, pages 485–490.

67. **J. Edward Swan II**, "A Brief Terrain Rendering Literature Review", Course Notes for *Volume Graphics*, Course 41, *Proceedings of the 26th International Conference on Computer Graphics and Interactive Techniques* (SIGGRAPH 1999), Los Angeles, CA, USA, August 8–13, 1999.

68. **J. Edward Swan II**, *Object-Order Rendering of Discrete Objects*. Doctoral Dissertation, Department of Computer and Information Science, The Ohio State University, Defended May 12, 1997.

69. Raghu Machiraju, **Edward Swan**, Roni Yagel, "Error-Bounded and Adaptive Reconstruction", *Newsletter of SPIE's International Technical Working Group on Electronic Imaging*, Volume 4, Issue 2, 1995.

70. Gregory J. Wiet, M.S., M.D.; David E. Schuller, M.D.; Joseph Goodman, M.D.; Don Stredney; Charles F. Bender, Ph.D.; Roni Yagel, Ph.D.; **J. Edward Swan II, M.S.**; Petra Schmallbrock Ph.D.; "Virtual Simulations of Brain and Cranial Base Tumors", *Proceedings of the 98th Annual Meeting of the American Academy of Otolaryngology—Head and Neck Surgery*, San Diego, California, USA, September 1994.

71. Don Stredney; Roni Yagel; Greg Wiet, M.D.; **Edward Swan**; Ferdi Sheepers, "Biomedical Simulations of High Performance Computing", *Presentation at the 103rd meeting of the Ohio Academy of Science*, Toledo, Ohio, USA, April 22–24, 1994.

72. D. Stredney, J. McDonald, G. Wiet, R. Yagel, E. Sindelar, **J.E. Swan**, "Virtual Simulations Through High Performance Computing", *Proceedings of Medicine Meets Virtual Reality II*, University of California, San Diego, California, USA, January 27–30, 1994, pages 212–215.

Technical Reports

73. *Chad A. Steed*, Patrick Fitzpatrick, T.J. Jankun-Kelly, **J. Edward Swan II**, "Visual Analysis of North Atlantic Hurricane Trends using Parallel Coordinates and Statistical Techniques," *Naval Research Laboratory*, *Stennis Space Center*, Mississippi, Technical Report #NRL/MR/7440--08-9130, July 7, 2008.

74. *Chad A. Steed*, Patrick Fitzpatrick, T.J. Jankun-Kelly, *Amber N. Yancey*, **J. Edward Swan II**, "An Interactive Parallel Coordinates Technique Applied to a Tropical Cyclone Climate Analysis," *Naval Research Laboratory*, *Stennis Space Center*, Mississippi, Technical Report #NRL/MR/7440--08-9126, June 6, 2008.

75. **J. Edward Swan II**, Mark A. Livingston, Harvey S. Smallman, *Joseph L. Gabbard*, Dennis Brown, Yohan Biallot, Simon J. Julier, Greg S. Schmidt, *Catherine Zanbaka*, Deborah Hix, Lawrence Rosenblum, "A Methodology for Quantifying Medium- and Far-Field Depth Perception in Optical, See-Through Augmented Reality", *Technical Report #MSU-050531, Department of Computer Science and Engineering, Mississippi State University*, May 2005.

76. **J. Edward Swan II**, Deborah Hix, *Joseph Gabbard*, "Perceptual and Ergonomic Issues in Mobile Augmented Reality for Urban Operations", *Naval Research Laboratory Memorandum Report*, 2003.

77. Greg S. Schmidt, **J. Edward Swan II**, *Derek Overby*, Lawrence Rosenblum, *Erik B. Tomlin*, "A System with Intelligent Editing for Extracting Ridge and Ravine Terrain Features", *Naval Research Laboratory Memorandum Report*, 2003.

78. **J. Edward Swan II**, Klaus Mueller, Torsten Möller, Naeem Shareef, Roger Crawfis, Roni Yagel, "Perspective Splatting", *Naval Research Laboratory Memorandum Report* NRL/MR/5580--99-8355, May 1999.

79. Baoquan Chen, **J. Edward Swan II**, Arie Kaufman, "A Hybrid LOD-Sprite Technique for Interactive Rendering of Large Datasets", *Center for Visual Computing Technical Report* TR981028, State University of Stony Brook, October 1998.

80. Shu-Chieh Wu, Jack W. Smith, **J. Edward Swan II**, "Pilot Study on the Effects of 3-D Reconstruction of Medical Images on Physician Diagnostic Decision", *Ohio State University Technical Report* LKBMS-TR-95-101, 1995.

81. Raghu Machiraju, **Edward Swan**, and Roni Yagel, "Spatial Domain Characterization and Control of Reconstruction Errors", *Ohio State University Technical Report* OSU-CISRC-4/95-TR17, April 1995.

82. Raghu Machiraju, **Edward Swan**, and Roni Yagel, "Error-Bounded and Adaptive Image Reconstruction", *Ohio State University Technical Report* OSU-CISRC-1/95-TR03, January 1995.

83. **J. Edward Swan II**, "Octree-based Collision Detection with Fast Neighbor Finding", *Ohio State University Technical Report* OSU-ACCAD-12/93-TR7, December 1993.

84. **J. Edward Swan II**, Roni Yagel, "Slice-Based Volume Rendering", *Ohio State University Technical Report* OSU-ACCAD-1/93-TR1, January 1993.

Patent Applications

85. *Chad A. Steed*, **J. Edward Swan II**, T.J. Jankun-Kelly, Patrick J. Fitzpatrick, "Information Assisted Visual Interface, System, and Method for Identifying and Quantifying Multivariate Associations", *Application for Patent*, (Navy Case 99713), US Patent Application Number 12/691,853, Filed January 22, 2010.

Technical Presentations

1. **J. Edward Swan II**, "Depth Perception in Augmented Reality: From AR Technology to Perceptual Science", Presentation to the *Hank Virtual Environments Lab, University of Iowa*, June 14, 2010. Host: Joe Kearney.

2. **J. Edward Swan II**, "Depth Perception in Augmented Reality: From AR Technology to Perceptual Science", Presentation to the *Visual Space Perception Laboratory, University of California, Berkeley*, March 12, 2010. Host: Martin S. Banks.

3. **J. Edward Swan II**, "Depth Perception in Augmented Reality: From AR Technology to Perceptual Science", Presentation to the *Human Systems Integration Division, National Aeronautics and Space Administration* (NASA), March 11, 2010. Host: Stephen R. Ellis.

4. **J. Edward Swan II**, "Empirically Evaluating a Hyperspectral Image Visualization Method: What Does Effectiveness Really Mean?", Presentation at the *Naval Research Laboratory*, *Stennis Space Center* (NRLSSC), May 7, 2009. Host: Chad Steed.

5. **J. Edward Swan II**, "Conducting Human-Subject Experiments", Presentation for Virtual Reality and Level-of-Detail Class (Electrical and Computer Engineering), *Mississippi State University*, April 16, 2009. Host: Phil Amburn.

6. **J. Edward Swan II**, "How to be a Successful Graduate Student: An Advisor's Perspective", Presentation for Department of Computer Science and Engineering Seminar Class (CSE 8011), *Mississippi State University*, April 1, 2009. Host: Ed Luke.

7. **J. Edward Swan II**, "Measurement Protocols for Medium-Field Distance Perception in Large-Screen Immersive Displays", Presentation at *IEEE Virtual Reality 2009*, Lafayette, Louisiana, USA, March 18, 2009. Host: Dirk Reiners.

8. **J. Edward Swan II**, "How to be a Successful Graduate Student: An Advisor's Perspective", Presentation to the Applied Cognitive Science Research Seminar, *Mississippi State University*, February 27, 2009. Host: Gary Bradshaw.

9. **J. Edward Swan II**, "How to be a Successful Graduate Student: An Advisor's Perspective", Presentation for Department of Computer Science and Engineering Seminar Class (CSE 8011), *Mississippi State University*, November 12, 2008. Host: Susan Bridges.

10. **J. Edward Swan II**, "Augmented Reality: Technology and Research Challenges", Presentation to Vice Commander Brigadier General (select) Tony Buntyn and Major Tim Franz, US Air Force Cyber Command, *Mississippi State University*, March 19, 2008. Host: Rayford B. Vaughn.

11. Joseph J. LaViola Jr., Doug A. Bowman, Stephen R. Ellis, Victoria Interrante, Benjamin C. Lok, **J. Edward Swan II**, "User Studies in VR: What Can We Learn From Them and What Are They Good For?", Panel Presentation at *IEEE Virtual Reality 2008*, Reno, Nevada, USA, March 10, 2008. Panel Organizer: Joseph J. LaViola Jr.

12. **J. Edward Swan II**, "Measuring the Effectiveness of Flow Visualization Techniques", Presentation to the Applied Cognitive Science Research Seminar, *Mississippi State University*, February 22, 2008. Host: Deborah Eakin.

13. Victoria Interrante, Dennis Proffitt, William Thompson, **J. Edward Swan II**, Joe Kearney, "Spatial Perception in Immersive Virtual Environments: New Theories and Current Controversies", Panel presentation at *IEEE Virtual Reality 2007*, Charlotte, North Carolina, USA, March 13, 2007. Panel Organizer: Victoria Interrante.

14. **J. Edward Swan II**, "Augmented Reality: Technology and Research Challenges", Presentation at the Security Awareness Briefing, sponsored by the Mississippi Infragard Program and the National Classification Management Society Magnolia Chapter, *Mississippi State University*, April 12, 2006. Host: David Dampier. **Invited presentation**.

15. **J. Edward Swan II**, "A Perceptual Matching Technique for Depth Judgments in Optical, See-Through Augmented Reality", Presentation at *IEEE Virtual Reality 2006*, Alexandria, Virginia, USA, March 27, 2006. Host: Benjamin Lok.

16. **J. Edward Swan II**, "Adaptation, Depth Perception, and X-Ray Vision in Optical, See-Through Augmented Reality", Presentation for MSU Department of Computer Science and Engineering Seminar Class (CSE 8011), *Mississippi State University*, November 11, 2005. Host: Ioana Banicescu.

17. **J. Edward Swan II**, "Depth Judgments in Optical, See-Through Augmented Reality", Presentation to the Applied Cognitive Science Research Seminar, *Mississippi State University*, October 7, 2005. Host: Carrick Williams.

18. **J. Edward Swan II**, "Adaptation, Depth Perception, and X-Ray Vision in Optical, See-Through Augmented Reality", Invited seminar presentation at *NASA Ames Research Laboratory*, Moffett Field, California, USA, July 28, 2005. Hosts: Steve Ellis, Bernard Adelstein. **Invited presentation**.

19. **J. Edward Swan II**, "Survey of User-Based Experimentation in Augmented Reality", Presentation at *HCI International 2005*, Las Vegas, Navada, USA, July 25, 2005. Host: Deborah Hix.

20. **J. Edward Swan II**, "Depth Perception and X-Ray Vision in Optical, See-Through Augmented Reality", Inaugural Presentation of the Institute for Neurocognitive Science and Technology (INST) Seminar Series (the first ever INST seminar), *Mississippi State University*, April 20, 2005. Host: Stephanie Doane.

21. **J. Edward Swan II**, "An Empirical User-Based Study of Text Drawing Styles and Outdoor Background Textures for Augmented Reality", Presentation at *IEEE Virtual Reality 2005*, Bonn, Germany, March 14, 2005. Host: Benjamin Lok.

22. **J. Edward Swan II**, "Depth Perception in Augmented Reality: Initial Results", Presentation for MSU Department of Computer Science and Engineering Seminar Class (CSE 8011), *Mississippi State University*, November 10, 2004. Host: Susan Bridges.

23. **J. Edward Swan II**, "Graphics and Visualization, Augmented and Virtual Reality", Presentation for meeting of representatives from Computer Science and Engineering (CSE) and the U.S. Army Engineer Research and Development Center / Information Technology Laboratory (ERDC/ITL), *Mississippi State University*, October 28, 2004. Host: Julia Hodges.

24. **J. Edward Swan II**, "Augmented Reality: Potential Applications and Research Challenges", Presentation at the National Science Foundation Industry / University Cooperative Research Center Organizational Meeting, *Mississippi State University*, Mississippi, September 22, 2004. Host: Ray Vaughn. **Invited presentation**.

25. **J. Edward Swan II**, "Empirical Measurement of Augmented Reality Display Techniques", Invited presentation at the *Department of Computer Science Seminar Series, George Mason University*, Fairfax, Virginia, USA, February 4, 2004. Host: Jim Chen. **Invited presentation**.

26. **J. Edward Swan II**, "Usability Engineering for Complex Interactive System Development", Presentation at the *Human Systems Integration Symposium 2003*, Vienna, Virginia, USA, June 24, 2003. Host: Dennis White. **Invited presentation.**

27. **J. Edward Swan II**, "Far-Field Occlusion and Distance Perception in Augmented Reality", Presentation at the *Office of Naval Research Workshop on Attention, Perception, and Modeling for Complex Displays*, Troy, NY, USA, June 6, 2003. Host: Astrid Schmidt-Nielsen.

28. **J. Edward Swan II**, "Interoperable Multi-Modal Interaction and Display System (IMMIDS)", *Office of Naval Research 6.2 Command and Control and Combat Systems Annual Review*, Booz Allen Hamilton, McLean, Virginia, USA, June 4, 2003. Host: Gary Toth.

29. Phil Cohen, **J. Edward Swan II**, "ARPAM: A Paper Map-Based C2 Interaction System using Augmented Reality & Digital Paper", *Office of Naval Research 6.2 Command and Control and Combat Systems Annual Review*, Booz Allen Hamilton, McLean, Virginia, USA, June 4, 2003. Host: Gary Toth.

30. **J. Edward Swan II**, "A Comparative Study of User Performance in a Map-Based Virtual Environment", Presentation at *IEEE Virtual Reality 2003*, Los Angeles, California, USA, March 26, 2003. Host: Bill Ribarsky.

31. Chadwick Wingrave, Dieter Schmalstieg, Doug Bowman, **J. Edward Swan II**, Steve Feiner, Mark Mine, "Mixed Reality: The Continuum from Virtual to Augmented Reality", Panel presentation at *IEEE Virtual Reality 2003*, Los Angeles, California, USA, March 25, 2003. Panel Organizer: Chadwick Wingrave.

32. **J. Edward Swan II**, “A Comparative Study of User Performance in a Map-Based Virtual Environment”, Presentation at the *University of Maryland at College Park Graphic Seminar Series*, College Park, Maryland, USA, March 19, 2003. Host: Amitabh Varshney. **Invited presentation**.

33. **J. Edward Swan II**, “Interoperable Multi-Modal Interaction and Display System (IMMIDS)”, *Office of Naval Research 6.2 Command and Control and Combat Systems Annual Review*, Marymount University, Arlington, Virginia, USA, April 24, 2002. Host: Gary Toth.

34. **J. Edward Swan II**, “Interactive, Distributed, Hardware-Accelerated LOD-Sprite Terrain Rendering with Stable Frame Rates”, Presentation at *Visualization and Data Analysis 2002*, Electronic Imaging 2002, Photonics West, San Jose, California, USA, January 22, 2002. Host: Jonathan C. Roberts.

35. **J. Edward Swan II**, “Interoperable Virtual Reality System”, *Office of Naval Research 6.2 Command and Control and Combat Systems Annual Review*, Marymount University, Arlington, Virginia, USA, May 24, 2001. Host: Paul Quinn. Presentation rated 3rd of all reviewed programs

36. **J. Edward Swan II**, “An Architecture for 3D/2D Multi-Modal Battlefield Interaction and Display Techniques”, *Office of Naval Research 6.2 Command and Control and Combat Systems New Start Reviews*, Marymount University, Arlington, Virginia, USA, May 24, 2001. Host: Paul Quinn. Presentation rated 4th out of 16 new start proposals.

37. **J. Edward Swan II**, “A Computational Steering System for Studying Microwave Interactions with Missile Bodies”, Presentation at *IEEE Visualization 2000*, Salt Lake City, Utah, USA, October 11, 2000. Host: Kelly Gaither.

38. **J. Edward Swan II**, “Interoperable Virtual Reality System”, *Office of Naval Research 6.2 Command and Control & Combat Systems Annual Review*, Naval War College, Newport, Rhode Island, USA, April 26, 2000. Host: Paul Quinn. **Presentation received the highest rating (1 out of 21) of all reviewed programs**.

39. **J. Edward Swan II**, Theresa-Marie Rhyne, David Laidlaw, Tamara Munzner, Victoria Interrante, “Visualization Needs More Visual Design!”, Panel presentation at *IEEE Visualization ’99*, San Francisco, California, USA, October 28, 1999. Panel Organizer: **J. Edward Swan II**.

40. Baoquan Chen, **J. Edward Swan II**, “LOD-Sprite Technique for Accelerated Terrain Rendering”, Presentation at *IEEE Visualization ’99*, San Francisco, California, USA, October 28, 1999. Host: Daniel Cohen-Or.

41. **J. Edward Swan II**, “Battlefield Augmented Reality System (BARS)”, Presentation at the *DoD Advanced Distributed Learning Workshop*, Arlington, Virginia, USA, October 5, 1999. Host: Pat Gorman. **Invited presentation**.

42. Larry Rosenblum, Simon Julier, **J. Edward Swan II**, “Virtual Reality Laboratory Research Program Outline”, Presentation to NRL’s Director of Research Timothy Coffey, *Naval Research Laboratory*, Washington, DC, USA, March 30, 1999. Host: Susan Numrich.

43. Simon Julier, **J. Edward Swan II**, “Interoperable Virtual Reality System”, *Office of Naval Research 6.2 Command and Control & Combat Systems Annual Review*, Noesis, Inc., Washington, DC, USA, March 24, 1999. Host: Paul Quinn.

44. **J. Edward Swan II**, “Image-Based Rendering Acceleration for Virtual Reality Systems”, *Office of Naval Research 6.2 Command and Control & Combat Systems Annual Review*, Noesis, Inc., Washington, DC, USA, March 24, 1999. Host: Paul Quinn.

45. **J. Edward Swan II**, “Battlefield Visualization on the Responsive Workbench”, Presentation at *IEEE Visualization ‘98*, Research Triangle Park, North Carolina, USA, October 22, 1998. Host: Michael Cox.

46. **J. Edward Swan II**, “Battlefield Visualization”, *Office of Naval Research 1998 Visualization Workshop*, Arlington, Virginia, USA, June 25, 1998. Host: Andre van Tilborg.

47. **J. Edward Swan II**, "Volume Graphics for Battlefield Visualization", *Office of Naval Research 6.2 New Start Proposal*, Naval Research Laboratory, Washington, DC, June 10, 1998. Host: Paul Quinn.

48. Simon Julier, **J. Edward Swan II**, "Human Centered Computing", *Office of Naval Research 6.2 Command and Control and Combat Systems Advanced Research Program Annual Review*, Naval Research Laboratory, Washington, DC, USA, June 9, 1998. Host: Paul Quinn.

49. **J. Edward Swan II**, "NRL VR Lab and Volume Graphics", Presentation to the *Visualization Laboratory of the Department of Computer Science at the State University of New York at Stony Brook*, Stony Brook, New York, USA, January 23, 1998. Host: Arie Kaufman. **Invited presentation**.

50. **J. Edward Swan II**, "An Anti-Aliasing Technique for Splatting", Presentation at *IEEE Visualization '97*, Phoenix, Arizona, USA, October 23, 1997. Host: Nelson Max.

51. **J. Edward Swan II**, "Experiences with 'Driving-Problem' Interdisciplinary Research", Presentation to the Research Group of *Chemical Abstracts Service (CAS)*, Columbus, Ohio, USA, May 28, 1996. Host: Wayne Johnson. **Invited presentation**.

52. **J. Edward Swan II**, "Relative Effects of Color-, Texture-, and Density-Coding on Visual Search Performance and Subjective Preference", Presentation at the *38th Annual Meeting of the Human Factors and Ergonomics Society* (HFES), Nashville, Tennessee, USA, October 25, 1994. Host: Karen J. Rafnel.

53. **J. Edward Swan II**, "The Determination of Wheelchair User Proficiency and Environmental Accessibility Through Virtual Simulation", Presentation at the *2nd Annual Conference on Virtual Reality and Persons with Disabilities*, Northridge, California, USA, June 9, 1994.

54. D. Stredney, J. Harris, **J. E. Swan II**, Beth Blostein, C. Hayes, "Determination of Environmental Accessibility and ADA Compliance Through Virtual Simulation", Educational Presentation at the *1994 Construction Expo*, Columbus, Ohio, USA, March 9, 1994.

Technical Demonstrations

55. Simon Julier, Yohan Baillot, Dennis Brown, Marco Lanzagorta, **J. Edward Swan II**, Steven Feiner, Blaine Bell, Elias Gagas, Sinem Guven, Drexel Hallaway, Tobias Hoellerer, Simon Lok, Navdeep Tinna, Ryuji Yamamoto, Andreas Butz, Eric Foxlin, Mike Harrington, Leonid Naimark, Dean Wormell, "Mobile Augmented Reality Systems", Emerging Technologies (Juried Exhibit), *SIGGRAPH 2001*, Los Angeles, California, USA, August 12–17, 2001. Also described in *Proceedings of the 28th International Conference on Computer Graphics and Interactive Techniques* (SIGGRAPH 2001), *Conference Abstracts and Applications*, page 129.

Teaching

Professional Tutorials

56. **J. Edward Swan II**, Bernard D. Adelstein, Joseph L. Gabbard, "Conducting Human-Subject Experiments with Virtual and Augmented Reality", Tutorial presented at *IEEE Virtual Reality 2009*, Lafayette, LA, USA, March 15, 2009. Course Organizer: **J. Edward Swan II**.

57. **J. Edward Swan II**, Mark A. Livingston, "Experimental Design and Analysis for Human-Subject Visualization Experiments", Tutorial presented at *IEEE Visualization 2008*, Columbus, OH, USA, October 20, 2008. Course Organizer: **J. Edward Swan II**.

58. **J. Edward Swan II**, "Experimental Design and Analysis for Human-Subject Visualization Experiments", Tutorial presented at *IEEE Visualization 2007*, Sacramento, CA, USA, October 28, 2007. Course Organizer: **J. Edward Swan II**.

59. **J. Edward Swan II**, Stephen R. Ellis, Bernard D. Adelstein, "Conducting Human-Subject Experiments with Virtual and Augmented Reality", Tutorial presented at *IEEE Virtual Reality 2007*, Charlotte, NC, USA, March 10, 2007. Course Organizer: **J. Edward Swan II**.

60. **J. Edward Swan II**, "Experimental Design and Analysis for Human-Subject Visualization Experiments", Tutorial presented at *IEEE Visualization 2006*, Baltimore, MD, USA, October 30, 2006. Course Organizer: **J. Edward Swan II**.

61. **J. Edward Swan II**, Stephen R. Ellis, Bernard D. Adelstein, "Conducting Human-Subject Experiments with Virtual and Augmented Reality", Tutorial presented at *IEEE Virtual Reality 2006*, Washington, DC, USA, March 25, 2006. Course Organizer: **J. Edward Swan II**.

62. Katerina Mania, Heinrich Bulthoff, Douglas Cunningham, Bernard D. Adelstein, Hyung Seok Kim, Nick Mourkoussis, Tom Troscianko, **J. Edward Swan II**, "Human-Centered Fidelity Metrics for Virtual Environment Simulation", Tutorial presented at *IEEE Virtual Reality 2005*, Bonn, Germany, March 12, 2005. Course Organizer: Katerina Mania.

63. **J. Edward Swan II**, Joseph L. Gabbard, Deborah Hix, Stephen R. Ellis, Bernard D. Adelstein, "Conducting Human-Subject Experiments with Virtual and Augmented Reality", Tutorial presented at *IEEE Virtual Reality 2004*, Chicago, Illinois, USA, March 28, 2004. Course Organizer: **J. Edward Swan II**.

64. Arie Kaufman, Milos Sramek, Sarah Gibson, Hanspeter Pfister, Yon Hardenbergh, Rick Avila, **J. Edward Swan II**, "Volume Graphics", Course presentation at *IEEE Visualization '99*, San Francisco, California, USA, October 24, 1999. Course Organizer: Arie Kaufman.

65. Arie Kaufman, Rick Avila, William Lorensen, Sarah Gibson, Hanspeter Pfister, Milos Sramek, **J. Edward Swan II**, "Volume Graphics", Course presentation at *ACM SIGGRAPH '99*, Los Angeles, California, USA, August 10, 1999. Course Organizer: Arie Kaufman.

University Courses (Mississippi State University)

year/term	**course number**	**course title**	**semester credits**	**number students**
2010/spring	CSE 4990/6990	Game Design	3	8/4*
2009/fall	CSE 2813	Discrete Structures	3	41
2009/fall	CSE 4833/6833	Introduction to Analysis of Algorithms	3	17/10*
2009/spring	CSE 2813	Discrete Structures	3	31
2008/fall	CSE 4833/6833	Introduction to Analysis of Algorithms	3	21/11*
2008/fall	CSE 4663/6663	Human-Computer Interaction	3	2/7*
2008/spring	CSE 4990/6990	Computer Game Design	3	6/11*
2007/fall	CSE 4663/6663	Human-Computer Interaction	3	6/12*
2007/fall	CSE 4833/6833	Introduction to Analysis of Algorithms	3	19/15*
2007/spring	CSE 8433	Advanced Computer Graphics	3	6
2006/fall	CSE 4663/6663	Human-Computer Interaction	3	7/15*
2006/fall	CSE 4833/6833	Introduction to Analysis of Algorithms	3	18/9*
2006/spring	CSE 8433	Advanced Computer Graphics	3	9
2005/fall	CSE 4833/6833	Introduction to Analysis of Algorithms	3	25/6*
2005/spring	CSE 8433	Advanced Computer Graphics	3	11

*number of undergraduate students / number of graduate students

University Courses (Ohio State University)

year/term	course number	course title	quarter credits	number students
1996/autumn	CIS 211	Computer Programming for Problem Solving	3	62
1996/summer	CIS 211	Computer Programming for Problem Solving	3	14
1996/spring	CIS 211	Computer Programming for Problem Solving	3	47
1996/winter	CIS 211	Computer Programming for Problem Solving	3	36
1995/autumn	CIS 211	Computer Programming for Problem Solving	3	58
1992/spring	CIS 222	Data Abstraction: A Second Course in Computer Science	4	11
1991/spring	CIS 100	Introduction to Computing Technology	3	11
1991/winter	CIS 100	Introduction to Computing Technology	3	26
1990/autumn	CIS 100	Introduction to Computing Technology	3	23

University Course Coordinator (Mississippi State University)

Responsible for maintaining ABET (Accreditation Board for Engineering and Technology) accreditation materials for the following courses:

- CSE 4833 Introduction to Analysis of Algorithms (3 credits)

Student Advising and Thesis Committee Service

Graduated PhD Students (Advisor / Co-Advisor):

- *Chad Steed* (Computer Science & Engineering), co-advisor with TJ Jankun-Kelley, “Development of a Geovisual Analytics Environment using Parallel Coordinates with Applications to Tropical Cyclone Trend Analysis”, Mississippi State University, PhD Dissertation, Fall 2008.
- *Joseph L Gabbard* (Computer Science; Virginia Polytechnic and State University), co-advisor with Deborah Hix (faculty at Virginia Tech), “Usability Engineering of Text Drawing Styles in Augmented Reality User Interfaces”, Virginia Polytechnic and State University, PhD Dissertation, Fall 2008.

Graduated PhD Students (Committee Member):

- *Byron Williams* (Computer Science & Engineering), “Change Decision Support: Extraction and Analysis of Late Architecture Changes Using Change Characterization and Software Metrics”, Mississippi State University, PhD Dissertation, Spring 2009.
- *Shangshu Cai* (Computer Engineering), “Hyperspectral Image Visualization Using Double and Multiple Layers”, Mississippi State University, PhD Dissertation, Fall 2008.
- *Baoquan Chen* (Computer Science), “Image-Based Volume Rendering”, State University of New York at Stony Brook, PhD Dissertation, October 1999.

Graduated MS Students (Advisor / Co-Advisor):

- *Gurjot Singh* (Computer Science & Engineering), “Near-Field Depth Perception in See-Through Augmented Reality”, MS Thesis, Summer 2010.
- *Alexander Morais* (Computer Science & Engineering), MS Project student, Summer 2009.
- *Dennon McMillian* (Computer Science & Engineering), MS Courses-Only, Fall 2008.
- *Brian Thomas* (Computer Science & Engineering), MS Courses-Only, Summer 2008.
- *Adam Jones* (Computer Science & Engineering), “Egocentric Depth Perception in Optical See-Through Augmented Reality”, MS Thesis, Summer 2007.

- *Joe Langley* (Computer Science & Engineering), co-advisor with Susan Bridges, “SCRIBE: A Clustering Approach to Semantic Information Retrieval”, MS Thesis, Spring 2006.

Graduated MS Students (Committee Member):

- *Andrew Stamps* (Computer Science & Engineering), MS Courses-Only, Spring 2010.
- *Mouthgalya Ganapathy* (Computational Engineering), “Obstacle Array Drag Coefficient Parametric Surface Response Analysis”, Fall 2009.
- *Yagneshwara Lanka* (Computer Science & Engineering), MS Courses-Only, Summer 2009.
- *Joel Martin* (Computer Engineering), “Results of a User Study on 2D Hurricane Visualization”, MS Thesis, Summer 2008.
- *David Wilson* (Computer Science & Engineering), “Analyzing Relationships in the Textual Contents of Digital Forensics Evidence”, MS Project, Spring 2008.

Current PhD Students (Advisor / Co-Advisor):

- *Teena Garrison* (Cognitive Science), “Applying Driving Simulation to Investigate Law Enforcement Officer Driving Behavior and Performance”, PhD student, expected 2010.
- *Adam Jones* (Computer Science & Engineering), “Egocentric Depth Perception in Augmented Reality”, PhD student, expected 2011.
- *Gurjot Singh* (Computer Science & Engineering), “Augmented Reality Implementation of X-Ray Vision”, PhD student, expected 2011.
- *Sujan Anreddy* (Computer Science & Engineering), topic not yet known, expected 2013.

Current PhD Students (Committee Member):

- *Yagneshwara Lanka* (Computer Science & Engineering), “Tensor Glyph Visualization Techniques”, PhD student, expected 2012.
- *Mark Thomas* (Cognitive Science), “Visual Processing and Object Memory”, Mississippi State University, PhD student, expected 2011.
- *Chevonne Dancer* (Computer Science & Engineering), “A Platform-Independent Investigative Process Model for Smartphones”, expected 2011.
- *David O'Gwynn* (Computer and Information Sciences; University of Alabama at Birmingham), “Semantic Alignment of Surface Meshes”, expected 2011.

Current MS Students (Advisor / Co-Advisor):

- *Josh Franck* (Experimental Psychology), “Depth Perception in Augmented and Virtual Reality”, MS student, expected 2011.

Undergraduate Research Advising:

- *Lorraine Lin* (Computer Science & Engineering), directed Summer Honors College Undergraduate Research Fellowship “Depth Perception in Augmented Reality”, Summer 2009; directed NASA-Funded Research “Development of Haploscope for Near-Field Depth Perception in Augmented Reality”, Summer 2010. Directed general lab involvement during the school year as well.
- *Huaiying (Shan Shan) Wang* (Brain & Cognitive Sciences; Massachusetts Institute of Technology (MIT)), directed summer research project “Development of Haploscope for Near-Field Depth Perception in Augmented Reality”, Summer 2010.

Previous Employment

The Naval Research Laboratory, Washington, DC, 1997–2004.

I was employed as a *Computer Scientist* by the *Virtual Reality Laboratory*, Code 5580, in the *Information Technology Division*. My primary activity was studying how humans can effectively utilize the emerging technologies of Augmented Reality (AR) and Virtual Reality (VR) for tasks of interest to the US Military, in particular battlefield situational awareness and visualization systems. This work involved empirically evaluating human subjects and integrating the resulting knowledge into theories of perceptual and cognitive behavior, developing and formalizing usability engineering methodologies for AR and VR interfaces, and researching, developing, and engineering specific AR and VR interaction techniques and associated software/hardware architectures.

Responsibilities: Conducting research and development at both Principal Investigator and Investigator levels; establishing and maintaining funding sources; sharing technical direction and leadership of a $2M/year laboratory; publishing, presenting, and demonstrating to academic, professional, and military communities; management and supervision of 1–3 full-time employees and 1–2 graduate student interns (usually over the summer); management of equipment acquisition and maintenance; professional service activities.

The Ohio State University, Columbus, Ohio, 1990–1997

Graduate Research Assistantships, 1991–1995: For a total of 16 quarters, I was supported by the following grants:

- Virtual Simulation of Brain and Cranial Base Tumors
- Online Steering of Scientific Simulations Using the NASA ACTS
- The Determination of Environmental Accessibility and Wheelchair User Proficiency Through Virtual Simulation
- Supercomputer Processing for Three Dimensional Brain Visualization
- Cognitive Theories of Intelligent Information Use

Graduate Teaching Assistantships, 1990–1996: For a total of 9 quarters, I taught the following undergraduate courses:

1995–96: *CIS 211: Computer Programming for Problem Solving.* Introduces the use of computers for problem solving; programming and spreadsheet assignments emphasize management-oriented problems. Assignments implemented in Pascal and a spreadsheet program. Intended for non-majors. I became overall course coordinator in 1996.

1992 *CIS 222: Data Abstraction: A Second Course in Computer Science.* Covers fundamental data structures; design, implementation, and use of abstract data types; recursion; and introduction to algorithm analysis. Programs developed in Modula-2. Intended for computer science majors.

1990–91: *CIS 100: Introduction to Computing Technology.* A course of general interest giving experience with personal computer software (word processors and spreadsheets); provides fundamental computer literacy; neither teaches nor requires computer programming. Intended for non-majors.

Other Previous Employment

1988–90: *Software Engineer***,** Optimization Technology Inc., Huntsville, Alabama.

1988: *Undergraduate Research Assistantship*, Auburn University, Auburn, Alabama.

1988: *Undergraduate Teaching Assistant*, Auburn University, Auburn, Alabama.

1986-87: *Management Assistant (Co-op Position)*, BellSouth Corporation, Birmingham, Alabama.

1983: *Management Assistant (Co-op Position)*, Southwire Corporation, Carrollton, Georgia.

Software Development

- *Experimental Counterbalancing Software*, with Joe Gabbard, Virginia Tech, 2001–2008. Co-developed a software architecture for separating the counterbalancing concerns of an experiment from the stimulus presentation concerns, and developed a series of counterbalancing programs, which have been used for all of the experiments conducted since 2001.
- *Augmented Reality Depth Study Software*, with Mark Livingston, Naval Research Laboratory, 2004. Co-developed a depth study module as part of the Battlefield Augmented Reality System, which we utilized to conduct a series of user-based, perceptual depth study experiments in Summer 2004.

- *Terrain Agent*, with Greg Schmidt, Naval Research Laboratory, 2002–2004. Co-developed software to allow pen-and-ink-based interaction with named areas on digital maps.
- *evalDragon*, Naval Research Laboratory, 1999–2001. Developed software to experiment with different navigation techniques in a map-based virtual reality system, which operated across different virtual reality platforms. Used software to conduct a user-based experiment in Spring 2001.

Service Activities

Affiliations

- IEEE, IEEE Computer Society, 1994–present.
- IEEE Computer Society Technical Committee on Visualization and Graphics: 1995–present.
- Association for Computing Machinery, SIGGRAPH and SIGCHI, 1992–present.
- American Society for Engineering Education, 2004–present.

Professional Service and Activities

Editorial Boards

- *Associate Editor*, International Journal of Human-Computer Studies, 2010–present.

Review Panels

- *National Science Foundation* (NSF) review panel, Washington DC, April 2010.
- *IEEE Virtual Reality 2010* International Program Committee, Waltham, Massachusetts, USA, March 20–24, 2010.
- *Naval Research Laboratory External Review Panel*, Battlespace Environments and Undersea Warfare Focus Areas (6.1 / 6.2) Marine Geosciences Research Program, Stennis Space Center, MS, USA, July 28–30, 2009.
- *International Symposium on Mixed and Augmented Reality* (ISMAR 2009) Science & Technology Area Chair (attended program committee meeting), Orlando, FL, USA, July 16–17, 2009.
- *National Science Foundation* (NSF) review panel, Washington DC, September 2008.
- *National Science Foundation* (NSF) review panel, Washington DC, January 2008.
- *National Science Foundation* (NSF) review panel, Washington DC, October 2007.
- *IEEE Virtual Reality 2006* Program Review Committee (senior reviewer who attends program committee meeting), chaired by Bernd Froehlich, Monterey CA, November 2005.
- *National Science Foundation* (NSF) review panel, Washington DC, June 2005.
- *National Science Foundation* (NSF) review panel, Washington DC, June 2005.
- *National Science Foundation* (NSF) review panel, Washington DC, June 2005.
- *IEEE Virtual Reality 2005* Program Review Committee (senior reviewer who attends program committee meeting), chaired by Bernd Froehlich, Washington DC, November 2004.
- *National Science Foundation* (NSF) review panel, Washington DC, October 2003.
- *National Science Foundation* (NSF) review panel, Washington DC, January 2003.
- *Office of Naval Research* (ONR) Small Business Innovative Research (SBIR) homeland defense proposals, topic N02-207/1, Washington DC, October 2002.

Program Chairmanships

- *IEEE Visualization 2002* (Program Co-Chair with Jim Thomas), Boston, Massachusetts, October 2002.
- *IEEE Visualization 2001* (Program Co-Chair with Hanspeter Pfister), San Diego, California, October 2001.

Program Committees

- *International Workshop on Mobile Collaborative Augmented Reality*, held in conjunction with ISMAR 2010, Seoul, Korea, October 13–16, 2010.
- *International Symposium on Mixed and Augmented Reality 2010* (ISMAR 2010), Seoul, Korea, October 13–16, 2010.
- *ACM Symposium on Virtual Reality and Software Technology 2010* (VRST 2010).
- *Applied Perception in Graphics and Visualization* 2010 (APGV 2010).
- *International Symposium on Visual Computing 2010* (ISVC 2010).
- *Conference on Visualization and Data Analysis 2010* (VDA 2010).
- *The 16th ACM Symposium on Virtual Reality and Software Technology 2009* (VRST 2009).
- *International Symposium on Visual Computing 2009* (ISVC09).
- *Conference on Visualization and Data Analysis 2009* (VDA 2009).
- *Conference on Visualization and Data Analysis 2008* (VDA 2008).
- International Program Committee for the *International Symposium on Mixed and Augmented Reality 2007* (ISMAR 2007).
- *Conference on Visualization and Data Analysis 2007* (VDA 2007).
- *IEEE Virtual Reality 2007* International Program Committee, Charlotte, North Carolina, USA, March 10–14, 2007.
- *International Symposium on Visual Computing 2006* (ISVC06).
- *Conference on Visualization and Data Analysis 2006* (VDA 2006).
- *IEEE Virtual Reality 2006* International Program Committee, Arlington, Virginia, USA, March 25–29, 2006.
- *IEEE Virtual Reality 2005* International Program Committee, Bonn, Germany, March 12–16, 2005.
- *International Workshop on Volume Graphics 2005*, Stony Brook, New York, USA, June 20–21, 2005.
- *Conference on Visual Data Exploration and Analysis 2005* (VDA 2005).
- *Conference on Visual Data Exploration and Analysis 2004,* Part of IS&T/SPIE International Symposium on Electronic Imaging 2004.
- *International Workshop on Volume Graphics 2003*, Tokyo, Japan, July 7–8, 2003.
- *IEEE Symposium on Information Visualization 2003,* Seattle, Washington, October 2003.
- *IEEE Symposium on Information Visualization 2002,* Boston Massachusetts, October 2002.
- *Conference on Visual Data Exploration and Analysis VIII,* part of SPIE and IS&T Electronic Imaging 2002.
- *International Workshop on Volume Graphics 2001*, Stony Brook, New York, June 2001.

Conference Committees

- *IEEE Virtual Reality 2011* posters co-chair, Singapore, March 2011.
- *IEEE Virtual Reality 2010* posters co-chair, Waltham, Massachusetts, USA, March 2010.
- *IEEE Virtual Reality 2006* workshops committee co-chair, Washington, DC, March 2006.
- *IEEE Visualization 2000* mini-workshops and birds-of-a-feather chair, Salt Lake City, Utah, October 2000.
- *IEEE Visualization ‘99* panels co-chair, San Francisco, California, October 1999.
- *IEEE Visualization ‘98* panels co-chair, Research Triangle Park, North Carolina, October 1998.
- *IEEE Visualization ‘97* mini-workshops and birds-of-a-feather chair, Phoenix, Arizona, October 1997.
- *IEEE Visualization ‘96* student volunteers co-chair, San Francisco, California, October 1996.

- *IEEE Visualization '95* student volunteers co-chair, Atlanta, Georgia, October 1995.

Other Professional Service

- *Search Committee Member* for the Editor-in-Chief of *IEEE Transactions on Visualization and Computer Graphics*, August–September 2010.
- *Session Chair*, "Papers Session 1: AR Studies", IEEE Virtual Reality 2010, Waltham, Massachusetts, USA, March 22, 2010.
- *Posters Fast-Forward Chair*, IEEE Virtual Reality 2010, Waltham, Massachusetts, USA, March 22, 2010.
- *Session Chair*, "Papers 2: 3DUI & AR/VR Systems", IEEE Virtual Reality 2007, Charlotte, North Carolina, USA, March 12, 2007.
- *Session Chair*, "Session 5: Evaluation and Perception", IEEE Virtual Reality 2006, Alexandria, Virginia, USA, March 28, 2006.
- *Session Chair*, "Studies III: Interaction and Collaboration", IEEE Virtual Reality 2005, Bonn, Germany, March 16, 2005.
- *Session Chair*, IEEE Visualization 2000, Salt Lake City, Utah, October 2000.
- *Newsletter Editor*, IEEE Computer Society Technical Committee on Visualization and Graphics, 1999.
- *Session Chair*, IEEE Visualization '98, Research Triangle Park, North Carolina, October 1998.
- *Student Volunteer*, IEEE Visualization '94, Washington, D.C., October 1994.
- *Student Volunteer*, IEEE Visualization '93, San Jose, California, October 1993.

University Service Activities

Academic and Committee Service to the University

- *Human Subjects Institutional Review Board* (IRB) (standing), Alternate Member, 2010–2013.
- Chair of the *Five Year Program Review for the Department of Psychology* (ad-hoc), convened for the Office of the Provost, 2010.
- *Steering Committee* (standing), Institute for Neurocognitive Science and Technology (INST), 2007–2011.
- *Courses and Curricula Committee* (standing), Department of Computer Science and Engineering, 2005–2011.
- *Strategic Planning Committee* (standing), Department of Computer Science & Engineering, 2009–2011.
- *Faculty Search Committee* (ad-hoc), Department of Computer Science and Engineering, 2008–2009.
- *Undergraduate Student Recruitment Committee* (standing), Department of Computer Science and Engineering, 2008–2009.
- *Rotation For Theory Courses Committee* (ad-hoc), Department of Computer Science and Engineering, 2008–2009.
- *PhD Qualifying Exam Study Committee* (ad hoc), Department of Computer Science and Engineering, 2008–2010.
- *Web Design Committee* (ad hoc), Department of Computer Science and Engineering, 2007–2008.
- *Senior Capstone Experience for Computer Science Majors* (ad hoc), Department of Computer Science and Engineering, 2007.
- *Graduate Studies Committee* (standing), Department of Computer Science and Engineering, 2006–2007, 2010–2011.
- *Facilities Committee* (standing), Department of Computer Science and Engineering, 2004–2008.
- *Seminar Committee* (ad hoc), Department of Computer Science and Engineering, 2004.

Musical Service to the University

- *Summer Scholars On Stage 2010*, Division of Academic Outreach and Continuing Education, July 18–24, 2010. Arranged music and played bass guitar in stage band.
- *Center for Autonomic Computing Bi-Annual Meeting Dinner* at the Hotel Chester, High Performance Computing Collaboratory, October 29th, 2009. Organized the After 5 Jazz Band, arranged music, sang and played bass guitar.
- *Latin American Night*, Program by the Hispanic Student Association, October 27th, 2009. Worked with Dr. Robert J. Damm (professor of music), assisted with musical arrangements, rehearsed with and taught the music to the students, and played bass guitar on nine songs.
- *Summer Scholars On Stage 2009*, Division of Academic Outreach and Continuing Education, July 19–25, 2009. Arranged music and played bass guitar in stage band.
- *African Night 2009, A Musical Safari to Africa*, Program by the African Student Association, February 22nd, 2009. Worked with Dr. Robert J. Damm (professor of music), assisted with musical arrangements, rehearsed with and taught the music to the students, served as sound engineer, provided the PA, and played bass guitar on nine songs.
- *Summer Scholars On Stage 2008*, Division of Academic Outreach and Continuing Education, July 19–26, 2008. Arranged music and played bass guitar in stage band.
- *Staff Appreciation Day 2008*, Professional and Support Staff Advisory Council, May 9, 2008. Organized Jukin' at the Junction band, sang and played guitar and bass guitar.
- *Celebrating African Night 2008*, presented by the African Students Association, February 24th, 2008, musical performance (bass guitar) on one song.
- *Faculty Recital*, Ms. Sheri Falcone, September 20th, 2007, musical performance (bass guitar) on three songs.
- *Student Recital*, Ms. Liz Tullos, April 22nd, 2007, musical performance (bass guitar) and teaching on two songs.
- *Faculty Recital*, Dr. Robert Damm, November 19th, 2006, musical performance (bass guitar) on one song.
- *Faculty Recital*, Ms. Sheri Falcone, September 27th, 2006, musical performance (bass guitar) on three songs.
- *Faculty Recital*, Dr. Jason Baker, August 27th, 2006, musical performance (bass guitar) on three songs.
- *Graduate Student Association* annual officer introduction event, April 28th, 2006, musical performance (bass guitar) with the *Mississippi Jazz Alliance*.
- *Faculty Recital*, Dr. Richard Human, April 6th, 2006, musical performance (bass guitar) on two songs, arranged one song.
- *MSU International Fiesta*, April 1st, 2006, musical performance (bass guitar, vocals) on three songs with the *Choral Relief Band* (arranged by Dr. Joe Ray Underwood).
- *President Lee's University Christmas Party*, December 9th, 2005, musical performance (bass guitar) with the *Choral Relief Band* (arranged by Dr. Joe Ray Underwood).
- *Faculty Recital*, Ms. Sheri Falcone, September 29th, 2005, musical performance (bass guitar) on three songs.
- *Department of Counseling Education annual departmental crawfish boil*, April 23rd, 2005, musical performance (bass guitar, vocals) with the *Choral Relief Band* (arranged by Dr. Joe Ray Underwood).

Professional Reviewing

- *Journal Referee*:
  ACM Transactions on Applied Perception
  Computers & Graphics
  IEEE Transactions on Visualization and Computer Graphics

IEEE Computer Graphics & Applications
PRESENCE: Teleoperators and Virtual Environments
Journal of Electronic Imaging in Visualization and Data Analysis
Journal of Electronic Imaging
International Journal of Human-Computer Studies
BMC Bioinformatics

- *Conference Referee*:
IEEE Virtual Reality 2010
IEEE Virtual Reality 2009
IEEE Virtual Reality 2008
IEEE Virtual Reality 2007
IEEE Virtual Reality 2006
IEEE Virtual Reality 2005
IEEE Virtual Reality 2004
IEEE Virtual Reality 2003
Virtual Reality Annual International Symposium (VRAIS) ‘98
IEEE Visualization 2008
IEEE Visualization 2007
IEEE Visualization 2003
IEEE Visualization 2001
IEEE Visualization 2000
IEEE Visualization ‘99
IEEE Visualization ‘98
IEEE Visualization Case Studies 2002
IEEE Visualization Case Studies 2001
IEEE Symposium on Information Visualization (InfoVis) 2007
IEEE Symposium on Information Visualization (InfoVis) 2003
IEEE Symposium on Information Visualization (InfoVis) 2002
IEEE Symposium on Information Visualization (InfoVis) 2001
ACM Computer-Human Interaction (CHI) 2005
IEEE TCVG Symposium on Visualization (VisSym) ’99
Visualization Late-Breaking Hot Topics ’99
ACM SIG CHI 2005: Conference on Computer-Human Interaction
Eurographics Workshop on Virtual Environments(EGVE) 2000
SPIE Conference on Visualization and Data Analysis 2009
SPIE Conference on Visualization and Data Analysis 2008
SPIE Conference on Visualization and Data Analysis 2007
SPIE Conference on Visualization and Data Analysis 2004
SPIE Conference on Visualization and Data Analysis 2003
SPIE Conference on Visualization and Data Analysis 2002
ACM Symposium on Virtual Reality Software and Technology (VRST) 2010
ACM Symposium on Virtual Reality Software and Technology (VRST) 2009
ACM Symposium on Virtual Reality Software and Technology (VRST) 2002
Applied Perception in Graphics and Visualization (APGV) 2010
International Workshop on Volume Graphics 2005
International Workshop on Volume Graphics 2003
International Workshop on Volume Graphics 2001
International Symposium on Mixed and Augmented Reality (ISMAR) 2010
International Symposium on Mixed and Augmented Reality (ISMAR) 2009
International Symposium on Mixed and Augmented Reality (ISMAR) 2007
International Symposium on Mixed and Augmented Reality (ISMAR) 2003
Eurographics Symposium on Virtual Environments Immersive Projection Technology Workshop 2007
International Symposium on Wearable Computing (ISWC) 2007

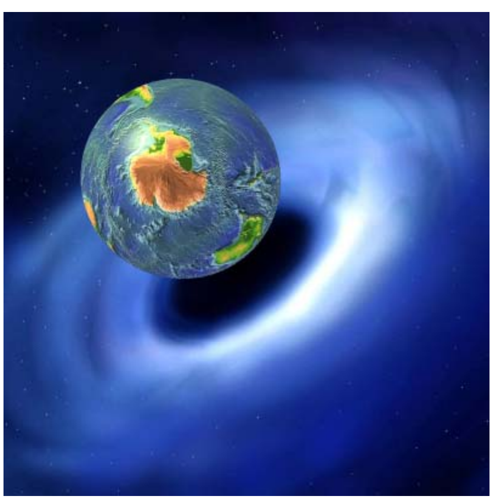
- *Proposal Referee*:
  Austrian Science Fund (Austrian equivalent of the National Science Foundation), 2006
- *Course Referee*:
  ACM SIGGRAPH ‘00
  ACM SIGGRAPH ’99
  ACM SIGGRAPH ‘98
  ACM SIGGRAPH ‘97
- *While a graduate student, reviewed advisor-refereed papers for the journals*:
  IEEE Computer Graphics and Applications
  IEEE Transactions on Computer Graphics and Visualization
  and for the conferences:
  Visualization ‘97
  Visualization ‘96
  Visualization ‘95
  Visualization ‘94
  Workshop on Volume Visualization 1996
  Workshop on Volume Visualization 1994
  SIGGRAPH ‘96
  SIGGRAPH ‘95
  SIGGRAPH ‘94
  Supercomputing ‘95

Workshops

- Participant in the *Workshop on Perceptual Multi-Modal Interfaces*, held at *IEEE Virtual Reality 2000* conference, New Brunswick, NJ, March 19, 2000.
- Invited participant in the *Office of Naval Research 1999 Multimodal Meeting*, Philadelphia, Pennsylvania, June, 1999.
- Invited participant in the *Office of Naval Research 1998 Visualization Workshop*, Arlington, Virginia, June 25–26, 1998.
- Invited participant in the *Office of Naval Research 1998 Multimodal Meeting*, Washington, DC, December 18, 1998.

J. Edward Swan II: Teaching Activities

Summary Statement



Amber Yancey
CSE 8433 Advanced Computer Graphics

Summary Statement

I knew I would enjoy teaching; in fact, the opportunity to teach was a large reason for leaving the Naval Research Laboratory in 2004 (where I had been employed since obtaining my PhD in 1997) and seeking an academic position. In March 2009 I was extremely gratified to be inducted into the *Bagley College of Engineering Academy of Distinguished Teachers*. The courses that lead to this award included an 8000-level graduate course (*Advanced Computer Graphics*), three 4000/6000 split-level courses (*Analysis of Algorithms*, *Human-Computer Interaction*, and *Game Design*), and a 2000-level undergraduate course (*Discrete Structures*). The student evaluations from each semester have been positive; in general, my scores have equaled or exceed the Computer Science and Engineering departmental averages, the College of Engineering averages, and the University averages. In this section I have included a chart which directly compares my evaluation scores to the departmental, college, and university averages. In addition to this quantitative feedback, I have encouraged students to give me feedback informally as class progresses. I believe I am generally aware of how students are doing in my classes, what is frustrating to them, and what they are enjoying. Finally, I have developed the habit of taking notes on what is and is not working during the semester, and then writing a self-evaluation narrative at the end of the semester, which describes both things that went well and things that could be improved next time. These self-evaluations are included in this section.

In Spring 2008, in collaboration with my colleague TJ Jankun-Kelly, I pioneered the course CSE 4/6990 *Computer Game Design*. Before initiating this course, students often expressed their interest in game design to me and my computer graphics colleagues. Computer games are a very important aspect of today's culture — especially youth culture — and furthermore a modern computer game is an extremely complicated and sophisticated engineering project, which also involves significant creative content that is most comparable to motion picture production. To date this course has been popular and has been offered three times, in Spring 2008 (taught by myself), 2009 (taught by Dr. Jankun-Kelly), and 2010 (taught by myself). During Spring 2010, I worked with the Mississippi wireless company Cellular South to provide 8 HTC Hero Android cell phones for game design projects. This partnership generated significant media interest; I was interviewed by Robbie Ward (University Relations) and Susan Lassetter (Bagley College of Engineering), which resulted in an MSU Press Release, two articles in The Clarion-Ledger, an article in the Delta Business Journal, and a report on WTVA news.

In previous years I revised the curricula for two courses: CSE 8433 *Advanced Computer Graphics*, and CSE 4/6990 *Human-Computer Interaction*. When I arrived both of these courses were listed, but had not been taught for several years. Therefore, I had to develop my own curriculum for both classes. In addition, I am pursuing ways to make Human-Computer Interaction more attractive to students from the College of Architecture, Art, and Design. This is motivated by current industrial trends, where interaction design is increasingly performed by multi-disciplinary teams, with backgrounds from design-related disciplines as well as computer science. Recruiting students with design backgrounds will create a learning environment that is closer to the way interaction design is performed in industrial settings.

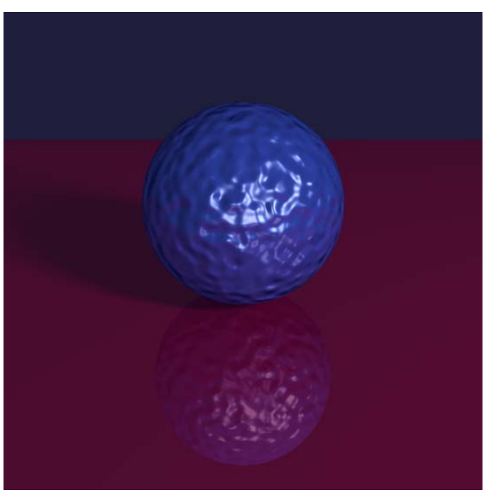
Beginning in Fall 2005, I have taught CSE 4/6833 *Analysis of Algorithms* every Fall semester. This is a core class which every Computer Science and Engineering (CSE), Software Engineering, and CSE graduate student has to take. It is somewhat traditional in CSE departments for faculty to always request full graduate courses, and to eventually be assigned a core class, but I wanted to contribute to the core curriculum from the beginning. I have found the class rewarding on several levels. A practical benefit of teaching a required core class is that it allows me to interact with a sizeable percentage of our undergraduate juniors and seniors, as well as graduate students from several different departments. It has also allowed me to recruit some excellent students for my research program.

I believe the following are the most innovative aspects of the courses that I've taught to date. These innovations are discussed in more detail in the self-assessments that appear later in this section.

(1) The lab sequence in Advanced Computer Graphics: For this class I developed a set of progressive programming assignments, where students systematically develop a ray tracer — a program that generates beautiful and intricate computer-generated images. The lab framework allows the class to cover the principals of computer graphics, while making the formulas practical (because the students must implement them) as well as supplying a context for the theoretical discussions (the theory explains why the images look the way they do). Furthermore, the students generate beautiful images, and this is very motivating — often students do more work than they really need to because they are excited. We also examine and discuss student images in class, and I post student images on my web site, which further motivates the students to generate images at least as cool as their peers'.

(2) The homework grading scheme in Analysis of Algorithms: In this class I encourage students to collaborate on homework assignments. On the day homework is due we spend the entire class period discussing the homework. Students then have up to 24 hours to turn in corrections for any problem that they didn't get completely right; the grading scheme is designed so that students can make up to 50% of their original grade from these corrections. This grading scheme encourages each student to really understand each homework problem, because they can get extra credit by continuing to improve their answer. However, it penalizes students who don't do the homework in the first place — such a strategy cannot yield a homework grade over 50%. Furthermore, this system encourages students to discuss the homework with each other, which I believe benefits both the student getting help and the student providing help.

(3) The projects in Human-Computer Interaction: The entire curriculum in this class is designed around class project assignments. During Fall 2008, students completed three project assignments in rotating teams. I gave the teams the option of either choosing a project from a list of projects that I supplied, or inventing their own project. For each of the three assignments one of the teams decided to invent their own project. I could tell that the teams were motivated to develop their own ideas, and these invented projects ended up being very good indeed! In Fall 2007 and Fall 2006 each project lasted for the entire semester, and involved outside customers. During Fall 2007, one project involved re-designing a web-based user interface for GoAnna, a tool developed by members of the Institute for Digital Biology (IDB) that is used to find protein descriptions in genomics databases. During Fall 2006 there were two external projects. The first was another collaboration with IDB; this project involved developing a user interface for a Gene Annotation Tool. The second project involved designing the user interface for the Challenge-X in-car display; this collaboration involved members of the Challenge-X team at CAVS. Overall, these external projects helped further the larger missions of both IDB and CAVS; both organizations could report supporting educational classroom activities to their funding agencies.



Chad Steed
CSE 8433 Advanced Computer Graphics

MISSISSIPPI STATE
UNIVERSITY

Bagley College of Engineering

February 13, 2009

Ed Swan
Computer Science & Engineering
MS 9637

Dear Ed:

Congratulations! You have been selected as one of the 2009 inductees into the Bagley College of Engineering Academy of Distinguished Teachers. You are to be commended for your excellent record in teaching, including the scholarship of teaching. We will celebrate your induction into the Academy of Distinguished Teachers with a dinner at Old Waverly on Wednesday, March 11 at 6:00pm. You are invited to bring a guest to celebrate your accomplishments. In addition, you will receive a stipend of $3,000 and have your name displayed on a plaque to be hung in McCain Hall.

As a part of being a winner of this college-level award, we will forward your packet for consideration for the Grisham Master Teacher award as well. These will be sent to the provost's office before the March 23rd deadline for that award. You will want to make sure that your packet adheres to the Grisham requirements that I will forward to you separately. Also, since fall 2008 teaching evaluations are now available, you will want to add these to your packet.

Congratulations again on this honor.

Sincerely yours,

Donna S Reese

Donna Reese
Associate Dean of Academics& Administration

Cc: Sarah Rajala
Julia Hodges

JAMES WORTH BAGLEY
COLLEGE OF ENGINEERING
MISSISSIPPI STATE UNIVERSITY

479-2 Hardy Road • 250 McCain Hall • Post Office Box 9544 • Mississippi State, MS 39762
dreese@bagley.msstate.edu • 662.325.0925 Phone • 662.325.8573 Fax • www.bagley.msstate.edu

J. Edward Swan II: Teaching Activities

Selected Support and Nomination Letters

These wonderful letters are selected from those that colleagues, students, and former students wrote in support of my 2009 Bagley College of Engineering Academy of Distinguished Teachers application.

Dr. Julia Hodges
Professor and Department Head
Department of Computer Science and Engineering

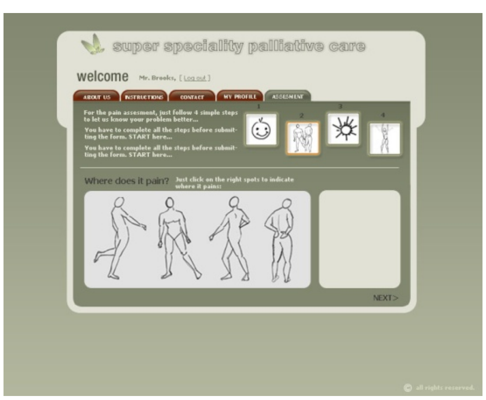
Dr. Susan Bridges
Professor and Co-Director of the Institute for Digital Biology
Department of Computer Science and Engineering

Amber N. Yancey
PhD Student
Department of Digital Production Arts, Clemson University, SC

J. Adam Jones
PhD Student
Department of Computer Science and Engineering

Dr. Chad Steed
Scientist
Naval Research Laboratory, Stennis Space Center, Mississippi

Joseph R. Langley
Scientist
Naval Research Laboratory, Washington, DC



Saurabh Dutta
Matthew Kolb
Juan Maldonado
CSE 4/6663 Human Computer Interaction

JAMES WORTH BAGLEY
COLLEGE OF ENGINEERING
MISSISSIPPI STATE UNIVERSITY
COMPUTER SCIENCE & ENGINEERING

Julia Hodges, Ph.D.
Professor and Department Head
Department of Computer Science and Engineering
Box 9637, 300 Butler Hall
Mississippi State, MS 39762-9637
Phone: (662) 325-2756 Fax: (662) 325-8997
hodges@cse.msstate.edu www.cse.msstate.edu

January 14, 2009

Selection Committee
James Worth Bagley Academy of Distinguished Teachers
Mail Stop 9544
MSU

To the Selection Committee:

I am pleased to provide a letter of support for the nomination of Dr. J. Edward (Ed) Swan II for the James Worth Bagley Academy of Distinguished Teachers. Ed is one of those exceptional faculty members who not only does research of the highest quality, but also is an outstanding classroom teacher. Ed is a very thorough individual who brings a lot of thought and creativity into his classes. He cares deeply about his students and takes very seriously his responsibility to provide them with a quality educational experience both inside and outside the classroom. He is willing to spend a lot of time outside of class helping students with something they don't understand or challenging them to think beyond the boundaries of the classroom.

Since joining our faculty in 2004, Ed has collaborated with other visualization faculty members to make major revisions that were needed to update our course offerings in computer graphics and visualization and to introduce new courses, including several that were offered as individual studies. Some of this effort involved Ed working very closely with faculty members from other departments, especially Psychology, to coordinate course offerings such as Human-Computer Interaction because they include concepts from both computer science and cognitive science. His collaborative efforts in both research and teaching have resulted in an adjunct faculty appointment in the Department of Psychology. Ed also worked with one of the other visualization faculty members to develop a new course in Computer Game Design.

I think of Ed as a true renaissance man. He is a talented musician in addition to being an excellent scientist and a wonderful teacher. I believe that it is this blend of talents and interests that is at least partly responsible for Ed's ability to enchant his students. His students describe his classes as energized, creative, detailed, organized, and entertaining. What a marvelous combination of skills from an organized, scientific mind that also sees the world through the eyes of an artist. His students talk about his ability to use completely different teaching styles for different kinds of courses and different kinds of students. They also describe him as very approachable, interested in his students, and respectful.

In addition to teaching courses in his specializations of graphics, visualization, and cognitive science, Ed has also been more than willing to teach introductory and upper-level general-purpose undergraduate courses. He has raised the bar of expectations for faculty members who teach these courses. As department head, I know that I do not need to worry about the quality of instruction in a course if I have assigned Ed to teach it.

Ed’s teaching abilities have been recognized by others in his field at a national and international level. He has been an instructor for ten tutorials at major conferences such as IEEE Visualization, IEEE Virtual Reality, and ACM SIGGRAPH. He has also received two teaching-related grants, one from NSF and one from the Schillig funds.

Ed deserves to be named to the James Worth Bagley Academy of Distinguished Teachers. I hope that you will give his nomination every consideration.

Sincerely,

Julia Hodges

Julia Hodges, Ph.D.
Professor and Department Head

JAMES WORTH BAGLEY COLLEGE OF ENGINEERING MISSISSIPPI STATE UNIVERSITY
COMPUTER SCIENCE & ENGINEERING

Susan Bridges, Ph.D.
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Mississippi State, MS 39762-9637
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bridges@cse.msstate.edu

January 15, 2009

Dr. Donna Reese
Associate Dean
Bagley College of Engineering

Dear Dr. Reese:

It gives me great pleasure to endorse the nomination of Dr. Ed Swan for membership in the Bagley College of Distinguished Teachers. I have served as Ed's mentor within the Department, have served on several committees with him, have co-directed a thesis with him, and have observed his presentations in the graduate seminar class.

Ed takes his teaching more seriously than just about any faculty member I have ever known. He is always extraordinarily well-prepared for class and always conveys his own enthusiasm about the technical material he is teaching. This is equally true for theoretical courses such as Algorithms and naturally exciting courses such as Game Design. You often hear faculty members complain that the only way to receive high student evaluations is to be an easy teacher. In my experience, the faculty members who receive the highest student evaluations are those who are truly interested in students, always fair, good communicators, and who have very high expectations. Ed meets all of these criteria—he receives some of the highest teaching evaluations in our department and has a reputation among students as one of the toughest teachers.

Last semester Ed volunteered to present a talk in the introductory graduate seminar class that I was teaching entitled "How to Be a Successful Graduate Student." I don't know if students appreciated the amount of time Ed invested in preparing for this one hour lecture, but I am convinced the seminar was of great benefit for our new graduate students. Ed started by presenting an analysis of why students pursue graduate degrees in computer science and supported his analysis with data. He encouraged students to analyze their own motivation for entering graduate school, discussed the major challenges students will encounter in completing their degrees, and presented concrete suggestions to help students with issues such as time management.

Ed and I co-directed the thesis of Joe Langley—one of the former students providing a letter of support for this application. Joe is an extremely bright student who struggled with depression throughout his undergraduate and graduate. Joe had an excellent idea for integrating graphics techniques with artificial intelligence techniques to design an innovative algorithm for information retrieval. Ed skillfully guided Joe through very difficult technical issues in graphics and statistical analysis and was adept at providing him with just the right balance of pep talks and challenges.

Ed has also made substantial contributions to the curriculum in CSE. He completely revised the content of both the Advanced Graphics course and the Human Computer Interaction course. I am most familiar with the Human Computer Interaction course because he has used projects from the Institute for Digital Biology and our AgBase database in this course. He successfully teaches students from completely different disciplines (e.g. computer science and cognitive science) in this class and the student projects that I have observed from the class are outstanding. The Game Design course that Ed developed with T.J. Jankun-Kelly has been enthusiastically received by our students. It is a pleasure to watch two talented teachers collaborate in an unselfish way to develop an exciting new course for our students.

Ed and I worked together to develop the questions for the computer science theory section of the qualifying examination for our Ph.D. students for several years. I was impressed by the effort that Ed invested in developing these questions and the great care he took to provide questions that were both challenging and fair. He observed a situation with qualifying exams at Ohio State when he was a graduate student that was unfair to students and he has never forgotten this experience. One of Ed’s great strengths as a teacher is that he constantly works to remember what it was like to learn a subject for the first time and to go through experiences such as qualifying examinations.

In addition to teaching students, Ed is also good at teaching professionals. The tutorials that he presents at graphics and visualization conferences on Conducting Human-Subject Experiments and Experimental Design are always well-received and he is invited to present these almost every year.

In conclusion, I believe that Ed is supremely qualified for the Bagley College of Distinguished Teachers and that his teaching is, and will continue to be, a credit to the Department of Computer Science and Engineering, to the Bagley College of Engineering, and to Mississippi State.

Sincerely

Dr. Susan Bridges
Professor

January 8, 2009

Dr. Donna Reese
Associate Dean for Academics & Administration
Chair, Bagley College of Engineering Academy of Distinguished Teachers
Selection Committee,

It is truly an honor to support Dr. J. Edward Swan II in his nomination into the James Worth Bagley Academy of Distinguished Teachers. Let it be known that this document is being submitted as a testament to the personal and professional character of Dr. Swan. I hold a strong belief in Dr. Swan and what he offers the university and in my opinion, there is no other professor that is as worthy of a nomination for such an honor.

As a former student at Mississippi State University, I have had the supreme pleasure of viewing Dr. Swan in several different lights. Not only have I taken a number of courses from him at MSU (CSE 8443 - Advanced Computer Graphics, CSE 6663 - Human-Computer Interaction, and CSE 8990 - Game Technology), but I have also had discussions with him at length on various subjects outside of class. Therefore, my insight may prove to be a valuable means of assessment. Looking back over the more than 250 hours of university coursework that I have completed over the years (at MSU and elsewhere) and all of the professors that have come with those courses, I am self-assured in declaring that Dr. Swan far outshines all other professors that I have had – ever. In all classes that I have taken from Dr. Swan, it has been evident that he devotes enormous amounts of time and energy into preparation for each class meeting. Examples of his preparation include the creation of detailed and entertaining PowerPoint presentations, in-class handouts, well-organized lectures and lecture notes, as needed based on the lecture topic. All in-class resources he makes readily available online and he keeps rigorously to a planned-out schedule to make sure all grounds for a given course are covered with adequate time before the semester ends. While he probably does not recognize that his efforts make a difference to his students, he nonetheless continues to put forth the same amount of preparation for every single lecture… and he does so without thanks because he is a devoted educator.

The three classes that I have taken with Dr. Swan were each very different. Each subject matter came with a different audience and hence Dr. Swan developed a different teaching style for each, as required. In the Human-Computer Interaction (HCI) course, in-class group work was required, so Dr. Swan provided groups with thought-provoking activities to help develop a good group dynamic. Advanced Computer Graphics was quite different with a different brand of students. Individual work was required for projects, but question-and-answer was encouraged every class before the lecture started and Dr. Swan always stayed around to answer individual questions after class. This class was the most interesting class that I took during my stay at MSU... it allowed for creativity, was incredibly challenging, yet was structured and everything about the subject was logical, thanks to the organization of the lectures. Our lectures were also recorded on video, so anything I didn't pick up in class, I could go back and watch again. This was infinitely useful to me. The Game Technology class encouraged out-of-class group work for the development of games. However, a great deal of fun was had in this course as we played, presented, and analyzed different styles of games within the class, did out-of-class game studies and shared with the class, and were motivated to try new things in our game development.

At MSU, while I was pursuing my graduate physics degree the last few years, I was taking a few computer science courses here and there to diversify myself. The majority of the time, when sitting in on physics lectures, I am ashamed to say that I found myself paying little to no attention in class because the professors were notorious for talking over students' heads – and by that, I mean that those professors had difficulty humbling their level of communication in order to communicate difficult material with students. This is not just the case in the physics department... I have experienced it in all departments. It seems that oftentimes, universities are so focused on getting good researchers that they fail to meet the necessity for good *educators* – shouldn't education be paramount? Well, Dr. Swan is an *excellent* educator. Period. To record, I have never witnessed anything other than a genuine desire and effort to communicate effectively and on the same level to whomever he is talking with. If you want students to learn, you must step back and gradually bring them up to the required knowledge level – Dr. Swan successfully implements this principle daily. In addition, he does it with style. So much of Dr. Swan's enjoyable personality, quirkiness, and sense of humor come across in his lectures (although I'm not sure he realizes it) that going to class was, shockingly, enjoyable and something that I anticipated from week to week! His ability to maintain the attention of the audience is second to none.

Intimidation is often something that I feel when approaching a professor to discuss something – anything. A few semesters ago, I approached Dr. Swan after class one day to discuss the course I was taking from him and to offer up some opinions and suggestions. Dr. Swan responded positively to a student taking interest in ways to potentially enhance his course. The following semester, Dr. Swan effectively changed his approach to take into consideration some of the things we had previously discussed. "Outstanding teachers engage in active assessment of the learning of their students and seek to improve their teaching to ensure even greater student learning in the future." I don't know how to effectively communicate to you the relief of not being intimidated when talking to a professor, but the bigger honor was having him respond to the suggestions and realize that a small change might benefit his courses. He has such a strong desire for feedback from his students, in addition to an open and honest communication channel; and as a student, it is satisfying to feel that your comments are appreciated. Dr. Swan has even been there for me when I needed an outlet for personal decisions concerning future goals and career choices. He has been a friend and mentor where others have failed and I cannot effectively express my gratitude for all that he has done in my life

Thank you for your time and attention. Please seriously consider Dr. Swan's nomination, as he is definitely a worthy individual.

Amber N. Yancey
Clemson University, Dept. of Digital Production Arts
ayancey@clemson.edu
662-617-0737

Dr. Donna Reese
Associate Dean for Academics & Administration
Chair, Bagley College of Engineering Academy of Distinguished Teachers Selection Committee

Dear Dr. Reese,

It is my privilege to nominate and lend my support to Dr. J. Edward Swan II, associate professor in the Department of Computer Science & Engineering, for induction into the James Worth Bagley Academy of Distinguished Teachers. I have taken many classes under Dr. Swan since he joined the MSU faculty and have witnessed the continued pattern of excellence for which he strives. Dr. Swan incorporates an interdisciplinary understanding of a course's material into his lectures and assignments, so that students following any number of academic paths may see the importance and impact of the education they are receiving. In the courses I have had with him, he engaged students in a combination of individual and group projects, as well as hands-on and theoretical exercises. It is this combination of individual reflection, group collaboration, practical application, and scholarly analysis that has aided me most in my education. I have come to admire Dr. Swan's ability to maintain open communication with his students as well. His door is always open to hear the questions, concerns, and discussions of his students. His courses consistently inspire my desire to not only learn the fundamentals of the subjects which he teaches, but also to develop a deeper understanding of their importance to my education. It is this very inspiration that makes his students aim for excellence both in and outside the classroom.

It is because of my experience in Dr. Swan's classes that I chose to request him to fill the role of my Major Professor for both my Masters and Doctoral programs. Through the years of studying under Dr. Swan, he has consistently challenged me to develop my skills as a scholar, scientist, and engineer. He is always willing to work to develop the best possible academic environment he can, while still holding fast to his high expectations for his students and advisees. He offers his students the flexibility to grow at their own pace, while maintaining a challenging and demanding academic environment. It is this pressure to expand beyond the students' comfort zones that allows each and every one of his students to leave his classrooms and labs as stronger, more confident individuals. It is for these reasons that I feel it has been an honor to study under the supervision and advisement of Dr. J. Edward Swan II.

Sincerely,

James Adam Jones

James Adam Jones
jaj33@cse.msstate.edu
PhD Student
Department of Computer Science & Engineering

Naval Research Laboratory
1005 Balch Blvd.
Stennis Space Center, MS
January 8, 2009

Dr. Donna Reese
Associate Dean for Academics & Administration
Chair, Bagley College of Engineering Academy of Distinguished Teachers
Selection Committee

Dear Dr. Reese:

I am writing this letter to support the nomination of Dr. J. Edward Swan II for induction into the James Worth Bagley Academy of Distinguished Teachers. During my recently completed doctoral study in the MSU Computer Science Department, I have been privileged to have Dr. Swan for my major professor as well as a teacher in two graduate classes.

First of all, Dr. Swan's excellent academic advisement skills illustrate that he is a distinguished teacher. The success and efficiency experienced in my Ph.D. pursuit is largely attributable to his superb academic advice. Furthermore, Dr. Swan offered career guidance as well as a wealth of encouragement and inspiration at key moments during my academic journey. His ability to relate to my circumstances and boundless enthusiasm were the key motivating factors that drove me to deliver my very best work.

Secondly, Dr. Swan's remarkable teaching skills reflect his place as a distinguished teacher. I am most impressed by his engaging communication style that conveys his passion for teaching and the hard work he dedicates to preparation. Although his classes were demanding, the sense of accomplishment was rewarding and he was always approachable and eager to help students grasp concepts completely. He actively encouraged collaboration among the students through traditional and online networking forums when appropriate. He also expressed remarkable humility and a natural ability to tie theory to real-world applications.

Finally, Dr. Swan is a remarkable role model for students and teachers alike. I greatly appreciate Dr. Swan's integrity, humility, easy-going demeanor, and generosity as well as the example of loving dedication he displays toward his family. Insomuch as I have been blessed to know Dr. Swan, I hope that I can be an equal blessing to others in the future. I am convinced, and I hope you agree, that Dr. Swan's embodiment of the honorable attributes sought for the James Worth Bagley Academy of Distinguished Teachers make him a very deserving inductee.

Sincerely,

Chad A. Steed, Ph.D.

8 January, 2009
Alexandria, VA

Dr. Donna Reese
Associate Dean for Academics & Administration
Chair, Bagley College of Engineering Academy of Distinguished Teachers
Selection Committee

Dr. Reese,

I write to you with great pleasure upon learning of Dr. Ed Swan's nomination for membership in the Bagley Academy of Distinguished Teachers. I can think of no better candidate for that distinction. Dr. Swan is an outstanding professor who comported himself excellently during his first years at Mississippi State – my final two. In his first course at MSU, Dr. Swan taught me advanced ray tracing and we delved those topics again the following year when he served on my thesis committee. In our correspondence since I graduated, I've seen that Dr. Swan is ceaselessly enthusiastic about learning; he is gifted at sharing that enthusiasm with his students. If I may take a few more minutes of your time, I'll share some of my strongest impressions of Ed's early professorship.

From the first day of his first class, I was struck by Dr. Swan's patient demeanor, keen descriptions, and attention to his students' individual strengths. Ed is soft-spoken and genial during lecture. His relaxed delivery belies an authoritative mastery of the subject matter owing to which he is free to monitor his students' dawning comprehension and continually adjust his pace. His style is almost conversational; his lecture flowed naturally into our questions and his answers transitioned smoothly back into the lecture. If I hadn't seen my fellows' confused faces light up in understanding, I would have thought their questions were scripted. I can only assume they felt the same watching me. We often asked him to describe the same concept twice from different perspectives, once mathematically and once qualitatively. His mathematical language was always precise, usually structured as outlines of constructive proofs of the underlying equations, and satisfied his students whose minds worked best in that mode. I was most impressed with his deconstruction of concrete examples into their visual components and his able mapping of those parts to the theories they embodied. He reinforced my appreciation of his teaching skills with every assignment. We all built the same basic software systems, ray tracing graphics renderers, but each with optional components constructed more easily from one frame of mind or the other – i.e., via rigorous mathematical programming or decomposition and abstraction. I could pass any assignment without stretching beyond my comfortable paradigm.

Achieving excellence, however, required me to work in that other, less familiar mode. Seeing Dr. Swan operate in his students' various mental models not only assured me that I could do the same, it inspired me to.

The following year, Dr. Swan served on my thesis committee. I owe him a great debt of gratitude for sticking with me while I pounded everything he'd just taught me about graphics into the non-visualizable niche of my research. Ed helped me maintain focus on the core of my research when I began to drift from fatigue. I often came to him with a distracting idea and after a few minutes of tossing it around he'd ask after my project with much more enthusiasm than he had for whatever bauble I'd brought to him. Subtly, he'd remind me that he was excited about my work and wanted to see it finished. He reflected my excitement from the days when I wrote my proposal; his gentle expectations reinvigorated me when I flagged.

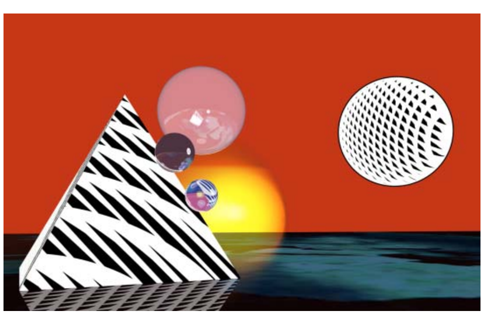
Dr. Swan's patience, insight, and love of learning bear on his studies, lessons, and mentorship with equal force. He is an uncommonly bright teacher who deserves our recognition. I support his nomination to the Academy and wholeheartedly recommend him to you.

Yours very respectfully,

Joseph R. Langley

J. Edward Swan II: Teaching Activities

Teaching Philosophy



Alex Morais
CSE 8433 Advanced Computer Graphics

Recognizing Excellent Teaching

I was an undergraduate engineering student at Auburn University. This was the first time that I really recognized and became inspired by examples of *excellent teaching*. For example, I remember a professor in one of my electrical engineering classes. In this class, we studied microcontrollers, especially in consumer devices such as, for example, washing machines. On the face of it, this doesn't seem as "cool" of a topic as, for example, compiler design, but I remember that during the lectures I and the other students were on the edges of our seats, hanging on every word. Why was that class so good? Because the professor gave such excellent lectures, and it was obvious that he thought the topic was very, very cool. This and similar experiences are when I began to realize that excellent teaching came from the professor, and not from the subject matter.

Since my undergraduate days, I have been an observer and a student of excellent examples of teaching. In no small part these examples of excellence, and the wonderful time I had as an undergraduate, are what inspired me to pursue a PhD and a career in academia. I still find examples of excellent teaching everywhere, especially when I attend talks, both on and off campus. I pay attention to what works and what does not work, and I continue to learn from it.

When I first arrived at MSU in 2004, Keith Hodge gave a talk during the new faculty orientation sessions about his teaching philosophy. At that point I already had 4 years of college teaching experience as a graduate teaching assistant at Ohio State. I found his talk very useful — it confirmed and gave labels to some of my own fuzzy observations — and I still occasionally look over his slides. Dr. Hodge's first and most central observation, which he calls "The Great Truth" and discusses on his first slide, is that students recognize excellent teaching when they experience it.

This forms the basis of my own teaching philosophy as well: I strive to be an *excellent* teacher. I know that my students recognize it when they experience it, and I recognize it when I experience it myself.

Principles of Excellent Teaching

Over the years that I have taught, I have developed some principals of excellent teaching. Each of these begins with the phrase "strive to", and this phrase is accurate: I always strive to achieve these goals, but through seeking feedback from students and peers, and upon self-reflection, I can always come up with ideas on how to do a better job the next time around.

Strive to communicate excitement and enthusiasm for the material: I have found that enthusiasm is the most important element of effective lecturing — if you are excited about the material, the excitement becomes infections, and the students become excited as well. This was Dr. Hodge's 2nd observation, but I had already experienced it when I arrived at MSU. I have found that the best way to generate this excitement is to remember what it felt like when I was a student who was first learning the material. I majored in computer science because, of all the cool things that I studied in college (and I spent 6 years considering a number of different majors, both within engineering and more generally), I found that I just loved the abstract, mathematical thinking of computer science. I strive to recapture this sense of wonder and excitement, and communicate it to my students.

Strive to understand the students' perception of the class: In particular, I believe it is very important to remember what it felt like to not yet understand the material. By connecting to this feeling, I find I can come up with many different ways of explaining something. Furthermore, it gives me patience, and helps me avoid the trap of becoming frustrated because a student doesn't understand something that I find simple — and students immediately sense this frustration and stop asking questions. I seek to understand my students' perception of the class primarily through frequent informal conversations, but I also obtain this understanding through student evaluations, and to a lesser extent, from grading exams and assignments.

Strive to organize the curriculum around homework, lab, or project assignments: I believe most people best learn by applying theoretical knowledge to some practical effort, and furthermore I have found that homework assignments, labs, and projects are the best way to get students to participate in classroom discussions — once students have themselves tried to accomplish something, they almost always have questions about it. Therefore, I strive to organize the lecture material around specific, practical assignments that the students must accomplish, and I have the first of these assignments due during the first several weeks of the semester. We spend significant amounts of classroom time discussing these assignments, and I expose students to theoretical concepts in the context of these discussions.

Strive to be honest when I don't know something: Although I generally have more knowledge than the students, I try to be honest when a student asks me something that I don't know. In such situations I'll usually ask if anyone else knows the answer, and often another student will. Through such exchanges I quickly gain insights about what the students already know, and who knows what. Also, the students pick up on the honesty and are more willing to speak up in class.

Strive to be very organized with the syllabus and schedule: I believe that students are very interested in predictability, especially when their grades are at stake. I spend a significant amount of time at the beginning of the semester developing the syllabus, which specifies the structure of the course. I post the syllabus and schedule as online documents, using the MyCourses web portal. The schedule is a living document; I use it to organize as much course material as possible — lecture notes, homework assignments, labs, upcoming due dates, and reading assignments. I update it every class period by linking the previous class's lecture notes, and I adjust the topic list to reflect what we actually covered in each class, as well as adjust future dates as they become clear. At the beginning of each class I show the schedule, and we talk about what has happened and what is coming up. This allows both the students and me to always know the current goals and current schedule.

Strive to grade promptly: Students really appreciate quick feedback, and they are more likely to be understanding when I cannot get something graded promptly if they know that I am usually prompt.

Strive to be fair, especially about grading: I don't think anything is as frustrating to students as perceived arbitrariness in grading. I always try to clearly explain how I've calculated grades. That said, I still find grading to be among the most difficult teaching tasks — especially in project-oriented classes, where the grading is necessarily subjective.

Standing on the Shoulders of Those Who Inspired Me

One of my favorite and most inspirational teachers at Auburn was Dr. Mel Phillips (now retired). He taught me a number of my most fascinating senior courses, including Formal Languages and Compiler Design. He is a master at communicating enthusiasm; he made everything seem cool and exciting. He also wrote one of the graduate school recommendation letters that allowed me to attend Ohio State. After several years at Ohio State, Dr. Phillips asked me to write a letter for him: he was applying for the Birdsong Teaching Award, which is an Auburn College of Engineering award that is the equivalent of the Academy of Distinguished Teachers award here[1]. I wrote him the letter, and I was *very* happy when I read that he had received the award — I felt that it was very well deserved. I am now *very* gratified and honored to have won the equivalent award — and my nominating students will verify that I did not ask them to nominate me — and to read the wonderful letters from students who seem to feel that I deserve this as I felt that Dr. Phillips deserved it. Reading these letters was the best thing that happened to me last year; they make all my efforts seem worthwhile.

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[1] At Auburn, the Birdsong Teaching Award has since been renamed the William F. Walker Teaching Award.

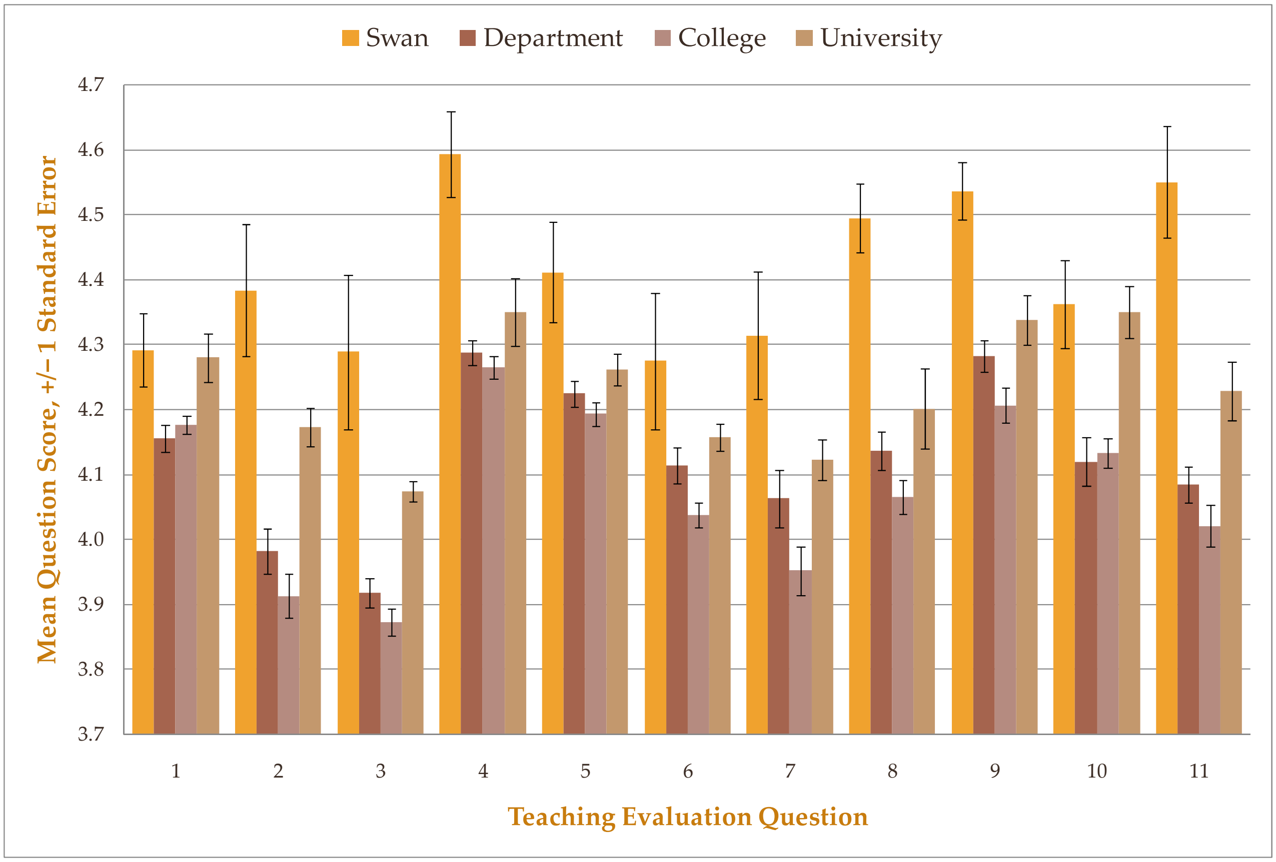
J. Edward Swan II: Teaching Activities

Summary of Student Teaching Evaluations

Jibonanada Sanyal
CSE 8433 Advanced Computer Graphics

Summary of Student Teaching Evaluations

This page summarizes my teaching evaluations for every course that I've taught at MSU, from Spring 2005 through Spring 2010. My evaluation scores are compared to those of the Department of Computer Science and Engineering, the College of Engineering, and the University; I collected these comparison scores every semester that they were available. From Spring 2005 through Spring 2010, no less than four different sets of evaluation questions were asked; for this analysis, I've mapped similar questions to the canonical 11 questions that are currently asked and that are shown here. This analysis indicates that my teaching evaluations typically equal or exceed the departmental, college, and university averages.



Teaching Evaluation Question		Swan	Depart-ment	College	Uni-versity
1	Created high expectations	4.29	4.16	4.18	4.28
2	Effectively conveyed course content	4.38	3.98	3.91	4.17
3	Made the class interesting	4.29	3.92	3.87	4.07
4	Enthusiastic about the subject matter	4.59	4.29	4.27	4.35
5	Was accessible outside class time	4.41	4.22	4.19	4.26
6	I learned a great deal	4.28	4.11	4.04	4.16
7	Presentation of content helped me learn	4.31	4.06	3.95	4.12
8	Tests were fair	4.49	4.14	4.07	4.20
9	Tests reflected lecture / reading material	4.54	4.28	4.21	4.34
10	Grading occurred within reasonable time period	4.36	4.12	4.13	4.35
11	Would recommend instructor to other students	4.55	4.08	4.02	4.23

Teaching Evaluation Raw Data

These pages contain the raw teaching evaluation data for all of the courses that I've taught at MSU; this is the data that is summarized on the previous page. Whenever the data was available, my evaluations are compared to the averages for the Department of Computer Science and Engineering, the College of Engineering, and the University. Note that four different sets of evaluation questions have been asked during the time that I've been teaching at MSU. For every semester that I've taught, my teaching evaluations have typically equaled or exceeded the departmental, college, and university averages.

Spring 2010

CSE 4/6990: Game Design (Special Topics)		**CSE 4/6990**	**Depart-ment**	**College**	**Uni-versity**
1	Created high expectations	4.5	4.2	4.2	4.4
2	Effectively conveyed course content	4.6	4.1	4.0	4.2
3	Made the class interesting	4.6	4.0	3.9	4.1
4	Enthusiastic about the subject matter	4.9	4.3	4.3	4.4
5	Was accessible outside class time	4.6	4.3	4.2	4.3
6	I learned a great deal	4.5	4.2	4.0	4.2
7	Presentation of content helped me learn	4.7	4.1	3.9	4.1
8	Tests were fair	4.8	4.2	4.1	4.1
9	Tests reflected lecture / reading material	4.8	4.3	4.2	4.3
10	Grading occurred within reasonable time period	4.6	4.3	4.2	4.4
11	Would recommend instructor to other students	4.9	4.2	4.1	4.2

Fall 2009

CSE 4/6833: Analysis of Algorithms *CSE 2813: Discrete Structures*		**CSE 4/6833**	**CSE 2813**	**Depart-ment**	**College**	**Uni-versity**
1	Created high expectations	4.4	4.5	4.2	4.2	4.3
2	Effectively conveyed course content	4.2	4.7	4.2	4.0	4.1
3	Made the class interesting	4.0	4.7	4.0	3.9	4.0
4	Enthusiastic about the subject matter	4.5	4.7	4.3	4.3	4.4
5	Was accessible outside class time	4.3	4.0	4.3	4.3	4.3
6	I learned a great deal	4.2	4.4	4.2	4.1	4.1
7	Presentation of content helped me learn	4.0	4.6	4.1	3.9	4.0
8	Tests were fair	4.5	4.7	4.2	4.1	4.1
9	Tests reflected lecture / reading material	4.4	4.7	4.3	4.3	4.3
10	Grading occurred within reasonable time period	4.2	4.5	4.2	4.2	4.3
11	Would recommend instructor to other students	4.4	4.8	4.2	4.1	4.2

Spring 2009

	CSE 2813: Discrete Structures	**CSE 2813**	**Depart-ment**	**College**	**Uni-versity**
1	Created high expectations	4.2	4.2	4.2	4.4
2	Effectively conveyed course content	4.3	4.0	4.0	4.2
3	Made the class interesting	4.2	3.9	3.9	4.1
4	Enthusiastic about the subject matter	4.5	4.3	4.3	4.5
5	Was accessible outside class time	4.4	4.2	4.2	4.3
6	I learned a great deal	4.2	4.1	4.0	4.2
7	Presentation of content helped me learn	4.2	3.9	3.9	4.1
8	Tests were fair	4.5	4.1	4.1	4.2
9	Tests reflected lecture / reading material	4.6	4.3	4.2	4.3
10	Grading occurred within reasonable time period	4.5	4.0	4.2	4.3
11	Would recommend instructor to other students	4.6	4.1	4.1	4.2

Fall 2008

	CSE 4/6833: Analysis of Algorithms *CSE 4/6663: Human-Computer Interaction*	**CSE 4/6833**	**CSE 4/6663**	**Depart-ment**
1	Created high expectations	4.2	4.3	4.2
2	Effectively conveyed course content	4.2	4.4	3.9
3	Made the class interesting	3.9	4.3	3.8
4	Enthusiastic about the subject matter	4.4	4.7	4.2
5	Was accessible outside class time	4.2	4.7	4.2
6	I learned a great deal	4.3	4.3	4.1
7	Presentation of content helped me learn	4.0	4.3	3.9
8	Tests were fair	4.4	4.6	4.0
9	Tests reflected lecture / reading material	4.5	4.5	4.2
10	Grading occurred within reasonable time period	4.2	4.6	4.0
11	Would recommend instructor to other students	4.5	4.7	4.0

Spring 2008

	CSE 4/6990: Game Design (Special Topics)	**CSE 4/6990**	**Depart-ment**	**College**	**Uni-versity**
1	Created high expectations	3.9	4.1	4.2	4.3
2	Effectively conveyed course content	4.0	3.9	3.9	4.2
3	Made the class interesting	4.1	3.8	3.9	4.1
4	Enthusiastic about the subject matter	4.5	4.2	4.3	4.4
5	Was accessible outside class time	4.1	4.2	4.2	4.3
6	I learned a great deal	3.6	3.9	4.0	4.1
7	Presentation of content helped me learn	3.9	3.9	3.9	4.1
8	Tests were fair	4.2	4.0	4.0	4.1
9	Tests reflected lecture / reading material	4.5	4.2	4.2	4.3
10	Grading occurred within reasonable time period	3.9	4.0	4.1	4.3
11	Would recommend instructor to other students	4.1	4.0	4.0	4.2

Fall 2007

	CSE 4/6833: Analysis of Algorithms *CSE 4/6663: Human-Computer Interaction*	**CSE 4/6833**	**CSE 4/6663**	**Depart-ment**	**College**	**Uni-versity**
1	Created high expectations	4.3	4.4	4.2	4.1	4.2
2	Effectively conveyed course content	4.7	4.7	4.0	3.9	4.2
3	Made the class interesting	4.2	4.4	3.9	3.8	4.1
4	Enthusiastic about the subject matter	4.4	4.6	4.4	4.2	4.4
5	Was accessible outside class time	4.3	4.6	4.3	4.2	4.2
6	I learned a great deal	4.3	4.3	4.1	4.0	4.1
7	Presentation of content helped me learn	4.4	4.5	4.0	3.8	4.1
8	Tests were fair	4.7	4.5	4.1	3.9	4.1
9	Tests reflected lecture / reading material	4.7	4.6	4.3	4.1	4.3
10	Grading occurred within reasonable time period	4.4	4.3	4.0	4.0	4.3
11	Would recommend instructor to other students	4.6	4.7	4.1	4.0	4.2

Spring 2007

CSE 8433: Advanced Computer Graphics		**CSE 8433**	**Depart-ment**	**College**	**Uni-versity**
1	Created high expectations	4.17	4.01	4.15	4.19
2	Effectively conveyed course content	4.83	4.03	4.01	4.27
3	Made the class interesting	5.00	3.94	3.94	4.03
4	Enthusiastic about the subject matter	5.00	4.34	4.31	4.08
5	I learned a great deal	4.83	4.10	4.03	4.19
6	Presentation of content helped me learn	4.33	4.03	3.95	4.22
7	Tests were fair	4.33	4.27	4.11	4.54
8	Tests reflected lecture / reading material	4.50	4.38	4.24	4.53
9	Grading occurred within reasonable time period	4.33	4.07	4.15	4.57
10	Would recommend instructor to other students	5.00	4.18	4.12	4.49

Fall 2006

CSE 4/6833: Analysis of Algorithms *CSE 4/6663: Human-Computer Interaction*		**CSE 4/6833**	**CSE 4/6663**
1	Created high expectations	3.90	4.16
2	Effectively conveyed course content	3.65	4.05
3	Made the class interesting	3.32	4.16
4	Enthusiastic about the subject matter	4.10	4.42
5	Was open to student questions	4.26	4.53
6	I learned a great deal	3.53	3.84
7	Course caused me to think	4.20	4.00
8	Presentation of content helped me learn	3.55	4.05
9	Visual aids could be clearly seen	4.40	4.32
10	Tests were fair	4.25	4.44
11	Tests reflected lecture / reading material	4.25	4.39
12	Grading occurred within reasonable time period	3.90	4.16
13	Spoke clearly and understandably	4.35	4.37
14	Created a positive learning environment	4.11	4.47
15	Would recommend instructor to other students	3.85	4.44

Spring 2006

CSE 8433: Advanced Computer Graphics		CSE 8433	Depart-ment	College
1	Makes the material interesting	5.00	3.96	3.94
2	Makes the material relevant	5.00	4.28	4.29
3	Communicates clearly	5.00	4.27	4.19
4	Is well organized	4.83	4.21	4.17
5	Knows if the course content is being understood	5.00	3.95	3.91
6	Is reasonably accessible outside of class	4.83	4.20	4.18
7	I have had to work hard in this class	4.50	4.11	4.14
8	I have become more competent	5.00	4.17	4.16
9	Grading and evaluation seem fair and objective	4.83	4.15	4.17
10	Would choose this instructor again	4.83	4.04	4.03

Fall 2005

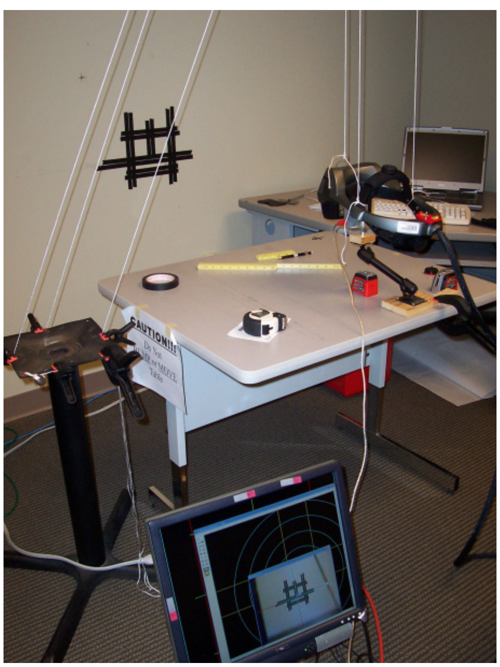
CSE 4/6833: Analysis of Algorithms		CSE 4/6833	Depart-ment	College
1	Makes the material interesting	3.75	3.95	3.79
2	Makes the material relevant	4.38	4.31	4.20
3	Communicates clearly	4.38	4.25	4.05
4	Is well organized	4.42	4.23	4.11
5	Knows if the course content is being understood	3.83	3.86	3.75
6	Is reasonably accessible outside of class	4.21	4.15	4.15
7	I have had to work hard in this class	4.25	4.15	4.16
8	I have become more competent	4.13	4.16	4.02
9	Grading and evaluation seem fair and objective	4.17	4.24	4.06
10	Would choose this instructor again	4.04	4.07	3.89

Spring 2005

CSE 8433: Advanced Computer Graphics		CSE 8433	Depart-ment	College	Uni-versity
1	Makes the material interesting	4.70	3.93	3.79	4.09
2	Makes the material relevant	4.80	4.25	4.19	4.27
3	Communicates clearly	4.80	4.18	3.98	4.24
4	Is well organized	4.60	4.19	4.07	4.28
5	Knows if the course content is being understood	4.60	3.88	3.75	4.04
6	Is reasonably accessible outside of class	4.70	4.17	4.12	4.17
7	I have had to work hard in this class	4.70	4.19	4.24	4.17
8	I have become more competent	4.70	4.11	4.03	4.21
9	Grading and evaluation seem fair and objective	4.50	4.11	4.05	4.27
10	Would choose this instructor again	4.80	3.95	3.85	4.11

J. Edward Swan II: Research Activities

Summary Statement



April 2009: A method we developed for optically calibrating an augmented reality head-mounted display. A computer camera sights the calibration pattern through the display's optics, where it is aligned using computer-generated calibration patterns. The suspension strings allow rotations around three orthogonal axes.

Research Program Description

I have desired a scientific career since I was in high school, and I have found Mississippi State University to be an excellent institution from which to conduct a research program. My research generally involves conducing human-factors investigations of computer-generated graphics. At MSU I have pursued the following research areas:

(1) Depth Perception in Augmented and Virtual Reality: I have been studying how depth perception operates in augmented and virtual reality for the past 8 years, beginning when I was employed by the Naval Research Laboratory. This work is currently supported by a single-PI NSF grant and a NASA grant, and beginning in October will be supported by a second single-PI NSF grant. Previously this work has been funded by NASA, the Office of Naval Research, and my startup resources. I have collaborated with colleagues from NASA Ames Research Center, NVIDIA Corporation, and the University of Rostock. Since my arrival at MSU, this work has resulted in a journal publication, 5 refereed conference publications, 7 other publications, and 2 completed master's theses. I am currently advising 3 PhD students in this area. My laboratory for this work is located at the Institute for Neurocognitive Science and Technology (INST).

(2) Human-Factors Aspects of Augmented and Virtual Reality and Simulator Technology: In addition to depth perception, I have been studying other human-factors aspects of augmented and virtual reality, including text legibility and cell-phone distraction for drivers. This work has primarily been in collaboration with colleagues from Virginia Tech and the Naval Research Laboratory. In addition, I am directing a Cognitive Science PhD student whose dissertation project uses the Driving Simulator at the Center for Advanced Vehicular Systems (CAVS). Since my arrival at MSU, this work has resulted in 3 journal publications, 5 refereed conference publications, and 3 other publications, as well as a completed dissertation (of a Virginia Tech graduate student).

(3) Visualization Technique Development and Evaluation: Since my arrival at MSU, I have worked on the development of new visualization techniques, with a special emphasis on the emerging area of conducting empirical evaluations. This research fills a niche at MSU, and allows me to apply my expertise in both human-computer interaction and visualization in a way that contributes to the long history of excellent visualization research at MSU. This work is collaborative with a number of MSU colleagues. It is currently funded by the National Science Foundation, and has previously been funded by the Department of the Army. In addition, one of my key graduate students in this area brought his own funding from the Naval Research Laboratory. Since my arrival at MSU, this work has resulted in 5 journal publications, 3 refereed conference publications, and 4 other publications, as well as 2 completed dissertations and a completed master's thesis.

At MSU my research activities have resulted in a total of 9 journal papers; on 6 of which either myself or one of my advisees is first author. They have also resulted in 13 refereed conference papers; on 7 of which either myself or one of my advisees is first author. Like other fields that have grown out of Computer Science, in my professional community these full-text refereed conference articles are widely read, have a professional impact that is comparable to journal articles, and have very low acceptance rates (the median for my papers is 28%). My research has also resulted in 12 abstracts and short papers, and has generated approximately 1.9 million in research funding.

I have consistently striven for quality in my research and the resulting publications. In Spring 2008 one of my journal papers won the *Bagley College of Engineering Outstanding Research Paper Award*, and in 2006 a conference paper won an *Honorable Mention* award at the IEEE Virtual Reality conference. Four additional papers that I published while at the Naval Research Laboratory received awards as well; two of these awards came from my employer and two from my professional societies (*Best Paper* awards at the IEEE Virtual Reality and IEEE Visualization conferences).

Finally, I enjoy collaborative work, and I believe the excellence I strive to bring to my interactions with students and colleagues is reflected in the large number of collaborators and coauthors that appear on my publications.

J. Edward Swan II: Research Activities

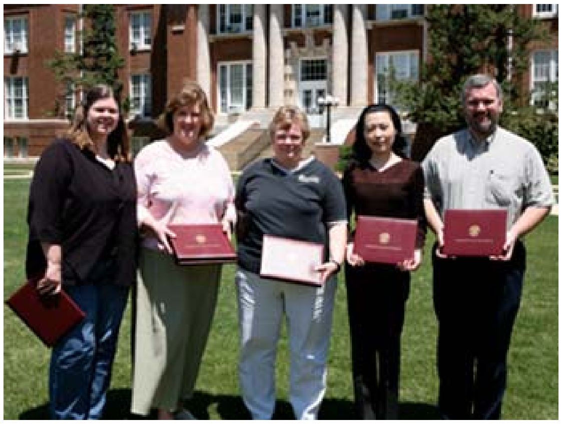
Awards and Distinctions

- **Bagley College of Engineering Outstanding Research Paper Award**, Spring 2008, Mississippi State University, for the publication "*Egocentric Depth Judgments in Optical, See-Through Augmented Reality*"

- Elected to **Upsilon Pi Epsilon**, April 18th, 2006, Mississippi State University

November 2008: An apparatus we engineered for measuring dark convergence. Our apparatus uses a nonius line technique, in which polarizing filters on the monitor and worn by the user allow each eye to see a different symbol on the screen; the keyboard allows the user to indicate when these symbols are in alignment, which yields an accurate measurement of the user's dark convergence. The equipment is covered in aluminum foil to eliminate illumination from dim internal lights on the circuit boards, which otherwise spoil the complete darkness required to take these measurements.

BCoE honors faculty



Several Bagley College of Engineering faculty members moved to the head-of-the-class recently after being named the recipients of this year's College of Engineering Faculty Awards. Presented as part of the annual BCoE Faculty and Staff Appreciation Day, the awards recognize achievements in both teaching and research.

Dr. Donna Reese, associate dean for academics and administration, received the Career Achievement Award. This is just the latest accolade in her storied career. Since joining the computer science and engineering (CSE) faculty in 1989 she has held numerous positions in the college. She has also been named a Grisham Master Teacher and Outstanding Faculty Advisor by the National Academic Advising Association.

Reese also was among those receiving this year's Outstanding Instructional Paper Award. She shared the award with fellow CSE department members Dr. Jeffrey Carver, assistant professor; Lisa Henderson, instructor; and department head Dr. Julia Hodges.

Other award recipients include Outstanding Educator, Dr. David Bridges, an associate professor in aerospace engineering; and Outstanding Researcher, Dr. Jenny Du, an associate professor in electrical and computer engineering. Dr. Ed Swan, associate professor in computer science and engineering, received the Outstanding Research Paper Award.

The College of Engineering Faculty Awards are presented each year to recognize the BCoE's world-class faculty, researchers and administrators. Congratulations to all of this year's BCoE award recipients.

News Archive...

Selected Publications

Note: PDF versions of all of my publications are on my Mississippi State University web page.

May 2007: Our augmented reality depth perception experimental setup. Participants performed blind walking depth judgments, during which they walked without sight to the previously seen targets. Blind walking has been widely used by vision scientists with both real-world targets and targets viewed in virtual reality; we have pioneered using the technique in augmented reality.

Selected Publications

These papers represent some of my proudest research accomplishments to date at MSU.

- *Chad A. Steed*, Patrick J. Fitzpatrick, T.J. Jankun-Kelly, *Amber Yancey*, **J. Edward Swan II**, "An Interactive Parallel Coordinates Technique Applied to a Tropical Cyclone Climate Analysis", *Computers & Geosciences*, July 2009, Volume 35, Issue 7, pages 1529–1539.

  This is the first journal article published by my first graduated PhD advisee Chad Steed. I began advising Chad after only 4 months at MSU; he graduated in December 2008. Our co-author Amber Yancey was also an MSU PhD student (she is currently a PhD student at Clemson).

- *J. Adam Jones*, **J. Edward Swan II**, *Gurjot Singh*, *Eric Kolstad*, Stephen R. Ellis, "The Effects of Virtual Reality, Augmented Reality, and Motion Parallax on Egocentric Depth Perception", *Proceedings of the Symposium on Applied Perception in Graphics and Visualization*, Los Angeles, California, USA, August 9–10, 2008, pages 9–14. Acceptance rate: 55%.

  This refereed conference article presents the first experiment completely conducted at the Augmented and Virtual Reality Laboratory that my students and I have built at MSU. It is also the first joint paper with my NASA Ames colleague Stephen R. Ellis, a long-time leading scientist in the field of augmented and virtual reality perception; I spent the summer of 2006 in Dr. Ellis' laboratory. We published it at an emerging and growing symposia dedicated to the confluence of computer graphics and perception.

- *Joseph L. Gabbard*, **J. Edward Swan II**, "Usability Engineering for Augmented Reality: Employing User-based Studies to Inform Design", *IEEE Transactions on Visualization and Computer Graphics*, May/June 2008, Volume 14, Number 3, pages 513–525.

  This invited, expanded journal article is the culmination of almost a decade of collaboration with Joseph Gabbard of Virginia Tech, an MS research scientist who also became my PhD co-advisee when he turned much of our joint work into a dissertation. I spent years cajoling him to "just write it up and finish"! He graduated December 2008.

- **J. Edward Swan II**, Adam Jones, Eric Kolstad, Mark A. Livingston, Harvey S. Smallman, "Egocentric Depth Judgments in Optical, See-Through Augmented Reality", *IEEE Transactions on Visualization and Computer Graphics*, Volume 13, Number 3, May/June 2007.

  This invited paper, which is an expansion of the award-winning paper listed below, received the **2008 Bagley College of Engineering Outstanding Research Paper** award.

- **J. Edward Swan II**, Mark A. Livingston, Harvey S. Smallman, Dennis Brown, Yohan Baillot, Joseph L. Gabbard, Deborah Hix, "A Perceptual Matching Technique for Depth Judgments in Optical, See-Through Augmented Reality", *Technical Papers, Proceedings of IEEE Virtual Reality 2006*, Alexandria, Virginia, USA, March 25–29, pages 19–26. Acceptance rate: 28%.

  This paper won an **Honorable Mention** award at *IEEE Virtual Reality 2006* as one of the three best Technical Papers presented at the conference. An extended version of the paper (above) was invited to be submitted to the May/June 2007 issue of *IEEE Transactions on Visualization and Computer Graphics*.

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An interactive parallel coordinates technique applied to a tropical cyclone climate analysis

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ABSTRACT

A highly interactive visual analysis system is presented that is based on an enhanced variant of parallel coordinates — a multivariate information visualization technique. The system combines many variations of previously described visual interaction techniques such as dynamic axis scaling, conjunctive visual queries, statistical indicators, and aerial perspective shading. The system capabilities are demonstrated on a hurricane climate data set. This climate study corroborates the notion that enhanced visual analysis with parallel coordinates provides a deeper understanding when used in conjunction with traditional multiple regression analysis.

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1. Introduction

In climate studies, scientists are interested in discovering which environmental factors influence significant weather phenomena. A prominent weather feature is a *tropical cyclone*, defined as a warm-core non-frontal synoptic-scale cyclone, originating over tropical or subtropical waters, with organized thunderstorms and a closed surface wind circulation. Tropical cyclones begin as a tropical depression, with sustained 10-m winds less than 17 ms^{-1}. Most intensify into *tropical storms* (sustained winds between 17 and 32 ms^{-1}). Fifty-six percent of tropical cyclones reach winds of at least 33 ms^{-1}, and are then designated with regional terms such as *hurricanes* in the Atlantic basin, and *typhoons* in the Western North Pacific Ocean. When sustained 10-m winds reach 49 ms^{-1}, they are called *intense hurricanes* in the Atlantic.

Tropical cyclone activity in each ocean basin can vary on a yearly scale as well as a multidecadal scale due to large-scale atmospheric influences and climate forcing. As a result, scientists are developing procedures to forecast whether an upcoming tropical cyclone season will be active, normal, or below normal. Others are studying causes of multidecadal cycles, and whether anthropogenic global warming is also an influence (Landsea, 2005). Recent destructive tropical cyclones seasons have escalated these research efforts.

Several atmospheric and climate variables impact the intensity and frequency of seasonal storm activity. Identifying the most critical environmental variables help scientists generate more accurate seasonal forecasts which, in turn, improve the preparedness of the general public and emergency agencies. One useful method for predicting and understanding the seasonal variability in tropical cyclones is multiple regression. Predictors are chosen from historical tropical cyclone data (Vitart, 2004), and provide an ordered list of the most important predictors for the dynamic parameters (Fig. 1).

In conjunction with statistical analysis, researchers have relied on simple scatter plots and histograms which require several separate plots or layered plots to analyze multiple variables. Using separate plots, however, is not an optimal approach in this type of analysis due to perceptual issues such as change blindness (a phenomenon described by Rensink, 2002), especially when searching for combinations of conditions. The scatter plot matrix is a more useful technique employed by statisticians to uncover patterns in multivariate data that contains all the pairwise scatter plots of the variables on a single display in a matrix configuration; but it requires a large amount of screen space and forming a multidimensional association from a set of two-dimensional displays is mentally challenging. Although layered plots condense the information into a single display, there are significant issues

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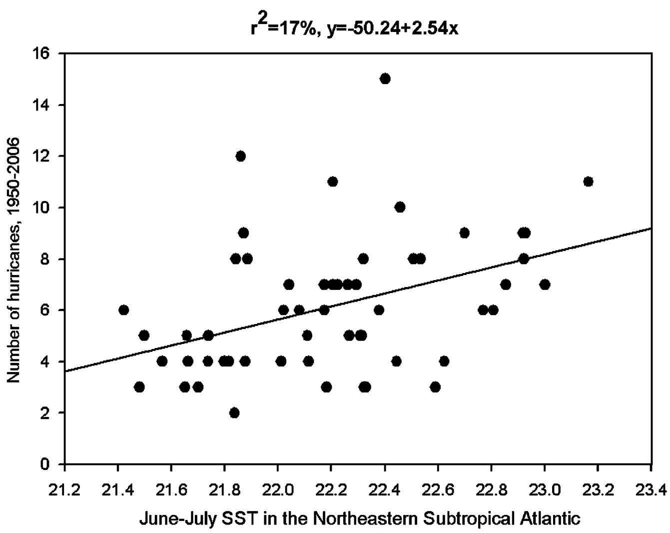

Fig. 1. Scatter plot with overlaid linear regression line is a common climate study visualization technique. Linear relationship between June–July SST (16) in northeastern subtropical Atlantic Ocean and number of hurricanes from 1950 to 2006 is shown. Explained variance is 17% (black-and-white).

Table 1
Interaction and representation features included in parallel coordinates visualization system developed in this research.

Focus + context	Interactively scales an axis and zooms into a subset of relations for that axis
Aerial perspective	Facilitates visual queries by shading lines based on proximity to the mouse cursor
Dynamic visual query	Explores multidimensional relationships with double-sided sliders
Statistical indicators	Indicates statistical quantities to support interaction model
Relocatable axes	Reorganizes the axes by dragging with the mouse to help to investigate variable associations
Axis inversion	Inverts the axis display scale by swapping the top and bottom values
Details-on-demand	Shows additional details for the highlighted axis, and displays the value on the axis scale under the mouse by clicking on the axis with the middle mouse button
Customizable display	Modifies the display (statistics display, color display, color schemes, tick marks) via a pop-up menu interface

due to occlusion and interference as demonstrated by Healey et al. (2004). Furthermore, the geographically-encoded data used in climate studies are usually displayed in the context of a geographical map; although certain important patterns (those directly related to geographic position) may be recognized in this context, additional information may be discovered more rapidly using non-geographical information visualization techniques. Due to the multivariate nature of climate study data, researchers need interactive visualization techniques that can accommodate the simultaneous display of many variables.

This paper discusses the application of a popular multivariate information visualization technique, parallel coordinates, to a tropical cyclone climate study and complemented by regression analysis. With parallel coordinates, n-dimensional data is represented as a polyline where its n-points are connected in n parallel y-axes. The resulting visualization provides a compact two-dimensional representation of even large multivariate data sets (Siirtola, 2000). In this research, several previously introduced interactive parallel coordinate extensions have been combined into an effective system for climate analysis. Table 1 summarizes the more significant extensions used in this work. This paper also discusses how these techniques increase the scientists' ability to discover the relationships between dependent and independent variables. Using a climate study data set that consists of several seasonal tropical cyclone predictors, it is shown that parallel coordinates provides a useful representation of multiple regression analysis. The results suggest that parallel coordinates can be used as an alternative method for finding relationships among a set of variables, and the technique can be used in conjunction with stepwise regression to enhance and speed up the relationship discovery process.

2. Related work

The parallel coordinates visualization technique was first introduced by Inselberg (1985) to represent hyper-dimensional geometries. Later, Wegman (1990) applied the technique to the analysis of multivariate relationships in data. Since then, several innovative extensions to the technique have been described in visualization research.

The system described in this paper implements a dynamic axis re-ordering capability, axis inversion, and some details-on-demand features similar to those described by Hauser et al. (2002). In addition, some interactive visual query and frequency representation (histogram) capabilities originally described by Siirtola (2000) and later refined in Siirtola and Räihä (2006) are included, as well as a variant of the interactive aerial perspective shading technique described by Jankun-Kelly and Waters (2006). The system also includes a focus+context technique for axis scaling that is similar to the capabilities described by Fua et al. (1999), Artero et al. (2004), Johansson et al. (2005b) and Novotný and Hauser (2006).

The system also provides dynamic query capabilities based on the double slider concept of Ahlberg and Shneiderman (1994). The PCP axes also display important frequency information between the double sliders in a manner similar to the Influence Explorer described by Tweedie et al. (1996). More recently, Siirtola and Räihä (2006) implemented these visual query mechanisms with parallel coordinates.

The visual analysis software described in this paper provides a powerful parallel coordinate based interface by fusing variants of the above mentioned capabilities. This paper provides one of the most in-depth case studies of enhanced parallel coordinate plots and the only instance of its application to hurricane trend analysis. Prior uses of parallel coordinates in the geosciences include a system described by Fua et al. (2000) that combines hierarchical parallel coordinates and a tree map for visualizing a large data set that was formed by combining SPOT, magnetics, and radiometric remote sensing data. In addition, Edsall (2003) used linked views, which included a parallel coordinates display, for climate modeling and analysis; and Johansson et al. (2005a) used meteorological data to demonstrate a new three-dimensional parallel coordinate representation. Similarly, Karki and Chennamsetty (2006) used parallel coordinates with several other linked views to explore large collections of mineral elasticity data.

Multiple regression traditionally has been used to identify statistically significant variables from multivariate data sets, including tropical cyclone data sets. Researchers at Colorado State University used this technique to determine the most important variables for predicting the frequency of tropical cyclone activity for the North Atlantic basin in 2006.[1] Similarly, Fitzpatrick (1996, 1997) applied stepwise regression analysis to the prediction of

[1] http://tropical.atmos.colostate.edu/Forecasts/2006/dec2006/

tropical cyclone intensity. It will be shown that multiple regression and interactive parallel coordinates can complement each other, with the regression identifying the relevant associations and the interactive software highlighting additional features of the variables.

3. Climate study data set

This research analyzes a data set containing potential environmental predictors for a tropical cyclone climate study. This data set was provided by the Tropical Meteorology Project at Colorado State University[2] and is used to predict the frequency of Atlantic tropical cyclones for the upcoming hurricane season by categories. These categories include: (1) number named storms (winds $17\,ms^{-1}$ or more, at which tropical cyclones receive a "name"); (2) number of hurricanes; and (3) number of intense hurricanes. These variables have known relationships to Atlantic tropical cyclone activity. For example, the North Atlantic basin has fewer tropical cyclones during El Niño Southern Oscillation (ENSO) years, and active seasons in La Niña years (Chu, 2004). Because of this relationship, scientists use ENSO signals as some predictors of seasonal storm activity. Scientists at the Tropical Meteorology Project issue six forecast reports based on statistically significant predictors from this data set.

Table 2 lists 16 potential environmental predictors from the data set along with their geographical region. In the remainder of this section, the physical relationships of these climate variables to Atlantic tropical cyclone activity are discussed.

Table 2
Environmental tropical cyclone climate variables evaluated as predictors in multiple regression procedure.

	Variable name	Geographical region
(1)	June–July Niño 3	5S–5N, 90–150W (eastern equatorial tropical Pacific Ocean)
(2)	May SST	5S–5N, 90–150W (eastern equatorial tropical Pacific Ocean)
(3)	February 200-mb U	5S–10N, 35–55W (equatorial East Brazil)
(4)	February–March 200-mb V	35–62.5S, 70–95E (South Indian Ocean)
(5)	February SLP	0–45S, 90–180W (eastern South Pacific Ocean)
(6)	October–November SLP	45–60N, 120–160W (Gulf of Alaska)
(7)	September 500-mb geopotential height	35–55N, 100–120W (western North America)
(8)	November SLP	7.5–22.5N, 125–175W (subtropical northeast Pacific Ocean)
(9)	March–April SLP	0–20N, 0–40W (eastern tropical Atlantic Ocean)
(10)	June–July SLP	10–25N, 10–60W (tropical Atlantic Ocean)
(11)	September–November SLP	15–35N, 75–97W (southeast Gulf of Mexico)
(12)	November 500-mb geopotential height	67.5–85N, 50W–10E (North Atlantic Ocean)
(13)	July 50-mb U	5S–5N, 0–360 (equatorial globe)
(14)	February SST	35–50N, 10–30W (northwest European Coast)
(15)	April–May SST	30–45N, 10–30W (northwest European Coast)
(16)	June–July SST	20–40N, 15–35W (northeast subtropical Atlantic Ocean)

3.1. El Niño variables

In a normal year, air rises in the western tropical Pacific (where the water is the warmest as well as slightly elevated) and sinks in the eastern tropical Pacific which is a phenomenon known as the Walker Circulation. During an El Niño event, the easterly surface trade winds that cause this water bulge in the western Pacific weaken, and the warm water travels eastward. Furthermore, El Niño conditions shift the upward portion of the Walker Circulation to the eastern Pacific, creating upper-level westerly winds in the Atlantic Ocean as well as subsidence. Both of these factors inhibit tropical cyclone formation and intensification in this region. Opposite conditions (abnormally strong trade winds and colder than normal eastern Pacific water) are called La Niña. La Niña years are associated with weak wind shear and little subsidence in the Atlantic, typically producing active tropical cyclone activity in this basin.

El Niño events are characterized by several possible variables. The *June–July Niño 3* (1) variable represents sea surface temperature (SST) anomalies of the eastern equatorial tropical Pacific Ocean. Positive values of this variable indicate an El Niño event, and negative represents a La Niña event. *May SST in the eastern equatorial Pacific* (2) represents a similar relationship. The first clues of an impending El Niño can be detected in February by observing three variables. Upper-level westerly (zonal) wind anomalies off the northeast coast of South America imply that the upward branch of the Walker Circulation associated with ENSO remains in the western Pacific and that El Niño conditions are likely to be present in the eastern equatorial Pacific for the next 4–6 months. This situation is measured by the *February 200-mb zonal wind (U) in equatorial East Brazil* (3). Likewise, anomalous late winter meridional (north) winds at 200-mb in the South Indian Ocean are also associated with El Niño conditions (*February–March 200-mb V in the South Indian Ocean* (4)). Finally, sea level pressure (SLP) in the eastern Pacific south of the equator is a measure of the trade winds whereby weak trade winds (or westerly surface winds) are associated with lower SLP and, therefore, El Niño conditions, while the opposite is correlated to La Niña conditions. Therefore, *February SLP in the eastern South Pacific* (5) is a possible variable. Some Fall variables are also correlated to El Niño conditions, such as the *October–November SLP in the Gulf of Alaska* (6), *September 500-mb geopotential height in western North America* (7), and *November SLP in the subtropical northeast Pacific* (8).

[2] P. Klotzbach, 2007, personal communication.

3.2. SLP variables

Pressure in the Atlantic Ocean is also inversely related to tropical cyclone activity, and seems to contain both monthly as well as longer term relationships. Low SLP in the tropical Atlantic implies increased atmospheric instability, moisture, and ascent (more favorable for the genesis of tropical cyclones), and weaker trade winds (which correspond to less wind shear that can tear up the thunderstorms in tropical cyclones). Low SLP in the spring tends to persist through the summer and fall. Therefore, potential variables include *March–April SLP in the eastern tropical Atlantic* (9), *June–July SLP in the tropical Atlantic* (10), and *September–November SLP in the southeast Gulf of Mexico* (11).

3.3. Teleconnection variables

The atmosphere is characterized by long-term oscillations which impact global wind patterns, known as teleconnections. Two of these are the Arctic Oscillation and the North Atlantic Oscillation. When these oscillations are in one phase, they cause more ridges in the Atlantic, which corresponds to less wind shear. Also, on decadal timescales, weaker zonal winds in the sub-polar areas are indicative of a relatively strong thermohaline circulation and therefore a warmer Atlantic Ocean. A variable which measures this oscillation is the *November 500-mb geopotential height in the North Atlantic* (12).

3.4. Quasi-biennial oscillation variable

Research has also shown that the Quasi-Biennial Oscillation (QBO) is correlated to tropical cyclone activity. The QBO is a stratospheric (16–35 km altitude) oscillation of equatorial east–west winds which vary with a period of about 26–30 months or roughly 2 years. These winds typically blow for 12–16 months from the east, then reverse and blow 12–16 months from the west, then back to easterly again. The west phase of the QBO has been shown to provide favorable conditions for development of tropical cyclones, possibly because it reduces wind shear. A variable which measures the QBO is the *July 50-mb Equatorial Wind (U) around the globe* (13).

3.5. Atlantic SST variables

The Atlantic SST is another major influence on tropical cyclone activity in that basin. Like SLP, winter and spring anomalies tend to persist throughout the season. Therefore, *February SST off the northwest European Coast* (14), *April–May SST off the northwest European Coast* (15), and *June–July SST in the northeast subtropical Atlantic* (16) are potential predictors. In addition, warm SST anomalies also tend to correlate with low SLP.

4. A dynamic interactive parallel coordinates application

To facilitate a deeper understanding of the climate data, a parallel coordinates application has been developed that fuses several previously introduced interactive extensions (see Table 1). In addition to fundamental PCP capabilities such as relocatable axes, axis inversion, and details-on-demand, this application provides several intuitive interaction capabilities such as axis scaling, aerial perspective shading, and dynamic visual queries. Since these individual capabilities are derived (with minor variations) from earlier research publications, the main contribution of this application lies in its collective capabilities and its application to climate analysis. In the remainder of this section, several of the visual analysis capabilities that are most valuable for climate studies are described in detail.

4.1. Dynamic visual queries

Since the viewer is often interested in grouping subsets of data, a method to select lines using double-ended sliders is provided for each axis (Siirtola and Räihä, 2006; Ahlberg and Shneiderman, 1994). As shown in Fig. 2, each axis has a pair of sliders (the large black triangles on each axis) which define the top and bottom range for the query area. Using the mouse cursor, the viewer can drag these sliders to dynamically adjust which lines are highlighted. Lines within the query area of every axis are rendered with a more prominent, dark color while the remaining lines are rendered with a less prominent, lighter shade of gray.

An example of a conjunctive query using the sliders is shown in Fig. 3. In this image, the sliders show only two storm seasons had an above average number of named storms but a below average number of intense hurricanes. In other words, when many named storms are observed, there tends to be an average or above average number of intense hurricanes as well.

4.2. Axis scaling (focus+context)

In displays where many relation lines are shown, it is often desirable to interactively tunnel through the relations until a smaller subset of the original data set is in focus. This application allows the user to modify the minimum and maximum values of the axes using the mouse wheel movement — a variation of previous axis scaling approaches (Fua et al., 1999; Artero et al., 2004; Johansson et al., 2005b; Novotný and Hauser, 2006).

On the axis bar, there are three distinct areas delineated by horizontal tick marks (Fig. 4) that are important to the axis scaling capability: the central focus area, and the top and bottom context areas. When the mouse is hovering over the focus area, an upward mouse wheel motion expands the display of the focus area

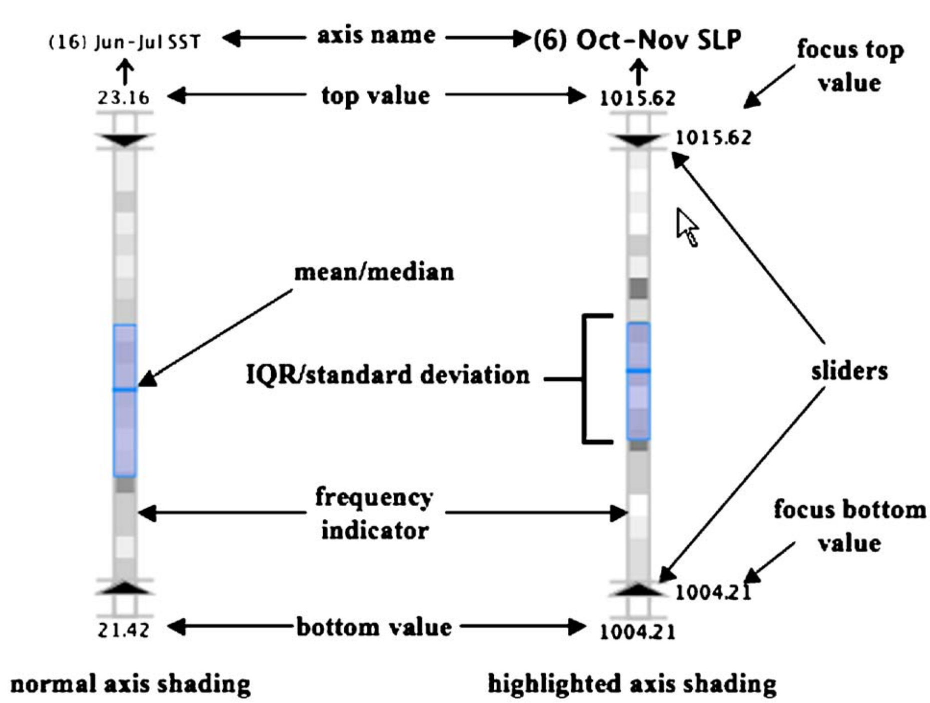

Fig. 2. Annotated view of parallel coordinates axis display widget. Normal axis shading (left) uses muted colors. When mouse is within an axis space (right), axis shading switches to highlighted representation (web: color, print: black-and-white).

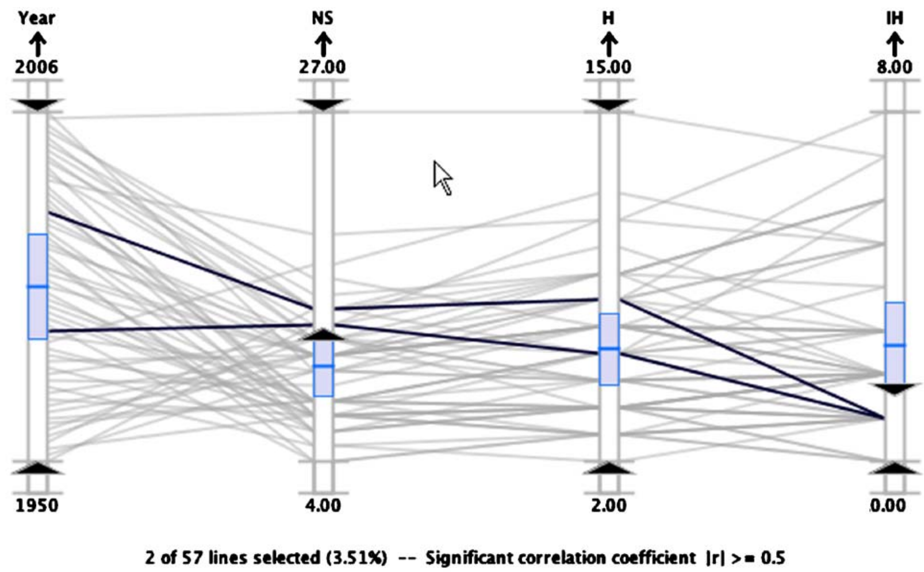

Fig. 3. Example of conjunctive query capability using dynamic query sliders for multiple axes. Sliders are set for above average range of Named Storms (NS) axis and below average range of Intense Hurricanes (IH) axis for data between 1950 and 2006. Two storm seasons fulfill this query criteria (web: color, print: black-and-white).

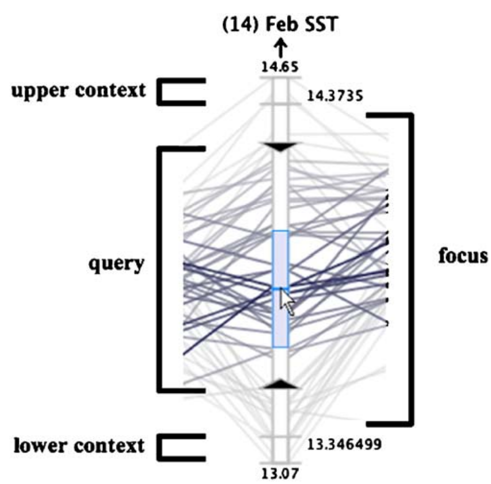

Fig. 4. Four distinct areas of axis display widget: query area, focus area, and upper and lower context areas (web: color, print: black-and-white).

outward and pushes outliers to the context areas (Fig. 5). A downward mouse wheel motion causes the inverse effect: focus region compression. Alternatively, the user may use the mouse wheel over either of the two context areas to alter the minimum or maximum values separately. The scaling capability frees space and reduces line clutter, thereby making it easier to analyze relation lines of interest.

4.3. Aerial perspective

The system also provides a proximity-based line shading scheme that is useful for quickly monitoring trends due to the similarity of data values over multiple dimensions (Siirtola and Räihä, 2006; Jankun-Kelly and Waters, 2006). This shading scheme simulates the human perception of aerial perspective whereby objects in the distance appear faded while objects nearer to the viewer seem more vivid. In this implementation, aerial perspective shading can be used in either a discrete or a continuous mode. In the discrete mode, the lines are colored according to the axis region that they intersect which is similar to the technique described by Siirtola and Räihä (2006). If any point of a relation line is in the context (non-focus) area of at least one axis, the line is shaded with a light gray color and drawn beneath the non-context lines (Fig. 5). If all the points on a relation line fall within the query area of each axis (the area between the two query sliders), the line is colored using a dark gray value that attracts the viewer's attention (Fig. 6). The remaining lines (non-query and non-context) are colored a shade of gray that is slightly darker than the context lines but lighter than the query lines.

In the continuous mode, non-context lines go through an additional step to encode the distance of the line from the mouse cursor in a manner similar to the approach described by Jankun-Kelly and Waters (2006). Query lines that are nearest to the mouse cursor are shaded with the darkest gray color while lines furthest from the mouse cursor are shaded with a lighter gray. The other query lines are shaded according to a non-linear fall-off function that yields a gradient of gray colors between extremes. Consequently, the lines that are nearest to the mouse cursor are more prominent to the viewer due to the more drastic color contrast and depth ordering treatments (Fig. 6) giving the viewer the ability to effectively use the mouse to perform rapid, visual queries.

4.4. Descriptive statistical indicators

To support the interactive analysis capabilities of the system, each axis offers visual representations of key descriptive statistics that are identified in Fig. 2 (Siirtola and Räihä, 2006; Hauser et al., 2002). The mean, standard deviation range, and the frequency information are calculated for the data in the focus area of each axis. Alternatively, the user can configure the system to display the median and interquartile range. All plots and analysis in this paper utilize the mean and standard deviation display mode. These central tendency and variability measures provide a numerical value that indicates the typical value and how "spread out" the samples are in the distribution, respectively. The axis box plots represent the descriptive statistics for all the samples within the focus area of the axis. In each axis interior, the frequency

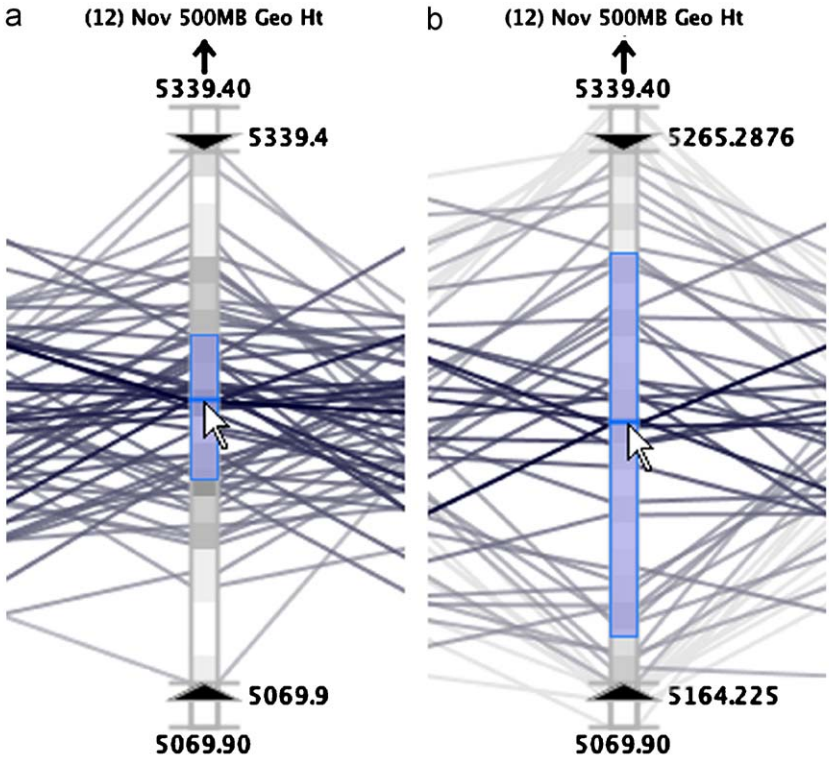

Fig. 5. Axis display widgets before (a) and after (b) dynamic scaling operation. Image sequence shows scaling effects after upward mouse wheel movement in focus area, which moves top and bottom limits closer together. Axis display is stretched upward and downward with base of display fixed (web:color, print: black-and-white).

information is also displayed by representing histogram bins as small rectangles with gray values that are indicative of the number of lines that pass through the bin's region (see Fig. 2). That is, the darkest bins have the most lines passing through while lighter bins have less lines. In Fig. 5, the histogram display is illustrated during an axis scaling operation.

5. Parallel coordinates validation: North Atlantic case study

As discussed previously, regression analysis is often employed to identify the most relevant climate relationships for tropical cyclone activity. Such techniques are effective in screening data and providing quantitative associations. However, multivariate analysis can be difficult. This section will outline how stepwise regression and parallel coordinates can complement each other in such an analysis.

Stepwise regression with a "backwards glance" is used which selects the optimum number of most important variables using a predefined significance value (90% in this study). Stepwise regression can assist visual analysis with parallel coordinates by isolating the significant variables in a quantitative fashion. An interactive parallel coordinates visualization can then be used to develop a deeper understanding of the complex relationships between the variables.

An extra step is taken to ensure the proper selection of variables. The initially chosen variables are examined for multicollinearity; if any variables are correlated with each other by more than the significant correlation threshold (0.5 in this study), one is removed and the code rerun. In this way, the chosen variables are truly independent of each other. The significant correlation threshold is a user defined value that is also displayed at the bottom of the parallel coordinate plot.

A normalization procedure is also executed for equal comparison between the variables. Denoting σ as the standard deviation of a variable, y as the dependent variable (named storms, hurricanes, or intense hurricanes in this study), $\bar{x}$ as the predictor mean, and $\bar{y}$ as the dependent variable mean, a number k of statistically significant predictors are normalized by the following regression:

$$(y-\bar{y})/\sigma_y = \sum_{i=1}^{k} b_i(x_i-\bar{x}_i)/\sigma_i \tag{1}$$

The advantage of this approach is that the importance of a predictor may be assessed by comparing regression coefficients b_i between different variables, and that the y-intercept becomes zero.

In addition, $\bar{x}_i$ may be interpreted (to a first approximation) as a "threshold" value which distinguishes between positive and negative contributions (for $b_i>0$), and the opposite for negative b_i. Years when independent variables contain large deviations from the mean could be associated with very active or inactive years, and require closer examination. As will be seen, the parallel coordinates technique facilitates the examination of active and quiet Atlantic hurricane seasons.

The 16 potential variables listed in Table 2 are examined in the stepwise regression, yielding several independent variables for each dependent variable. These results show that several climate factors impact tropical cyclone activity. The chosen predictors are shown in Table 3, along with their normalized regression coefficient and sample mean. The explained variance (R^2) is shown in the three table headings.

The stepwise regression shows only one significant El Niño variable (late winter South Indian Ocean 200-mb meridional winds (4)) impacts total number of storms; it is the second most influential predictor. Late winter northwest coastal European SST (14) is the leading predictor. The North Atlantic Oscillation (manifested by 500-mb geopotential height in the North Atlantic (12)) ranks third, and is also the only variable seen in all three

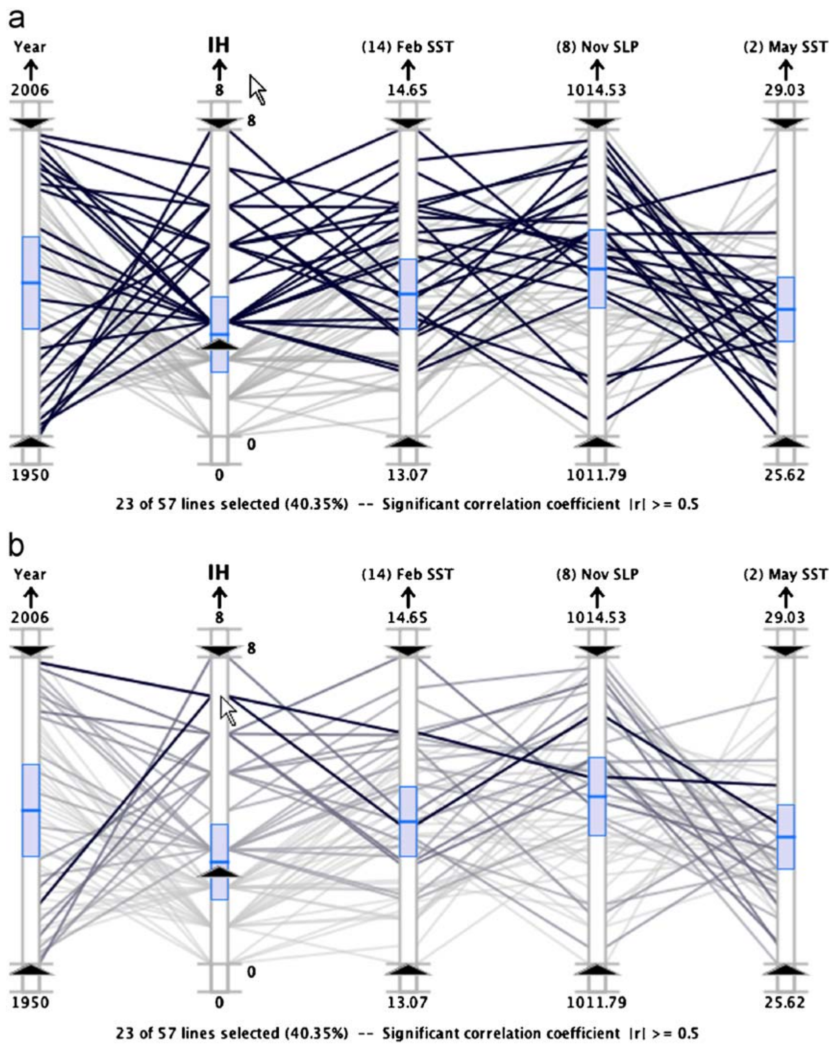

Fig. 6. Aerial perspective shading can be used in either discrete (a) or continuous (b) mode. Line colors are assigned based on line location with respect to context, focus, and query areas of axes. In continuous mode, line distance from mouse cursor is also encoded with color value. Figures show mouse cursor positioned at top of second axis, which highlights seasons with above average intense hurricane activity (web: color, print: black-and-white).

Table 3
Significant climate variables chosen from Table 2 by stepwise regression for number of named storms, hurricanes, and intense hurricanes in 1950–2006.

Chosen variables	Normalized coefficients *c*	Sample mean
Number of Named Storms (NS) (R^2 is 34%)		
February SST (14)	0.302	13.8
February–March 200-mb V (4)	−0.244	2.5
November 500-mb geopotential height (12)	0.232	5213.0
September–November SLP (11)	−0.175	1015.0
Number of Hurricanes (H) (R^2 is 42%)		
October–November SLP (6)	−0.284	1009.6
June–July SST (16)	0.259	22.2
November 500-mb geopotential height (12)	0.258	5213.0
September–November SLP (11)	−0.208	1015.0
Number of Intense Hurricanes (IH) (R^2 is 54%)		
November 500-mb geopotential height (12)	0.345	5213.0
June–July SLP (10)	−0.315	1016.2
September 500-mb geopotential height (7)	0.292	5753.3
February SST (14)	0.235	13.8

Also shown is explained variance R^2, normalized coefficients *b*, and sample mean.

tables. This suggests that the presence of a ridge in the Atlantic is conducive to an above average tropical cyclone season. Finally, low SLP in the southeast Gulf of Mexico (11) also encourages the formation of tropical cyclones. Note that the coefficient has a negative sign, showing that the lower the pressure, the better the chance of tropical cyclone activity.

For number of hurricanes, the analysis surprisingly shows that October–November SLP in the Gulf of Alaska (6) is the most important predictor. The physical role is not clear, although scientists know it is correlated to El Niño activity. Northeast subtropical Atlantic SST (16) and North Atlantic 500-mb geopotential height (12) are tied for second, and southeast Gulf SLP again ranks fourth (11). The explained variance is 42% — more than the 34% for named storms. This suggests stronger predictor relationships for number of hurricanes.

For intense hurricanes, the variance increases to 54%. In this case, the North Atlantic November 500-mb height variable (12) is the strongest predictor. Early summer tropical Atlantic SLP (10) ranks number two, followed by September 500-mb geopotential height in western North America (7) and February SST off northwest coastal Europe (14). The higher variance and distinctly different chosen predictors suggests different environmental influences are required for intense hurricanes. This analysis

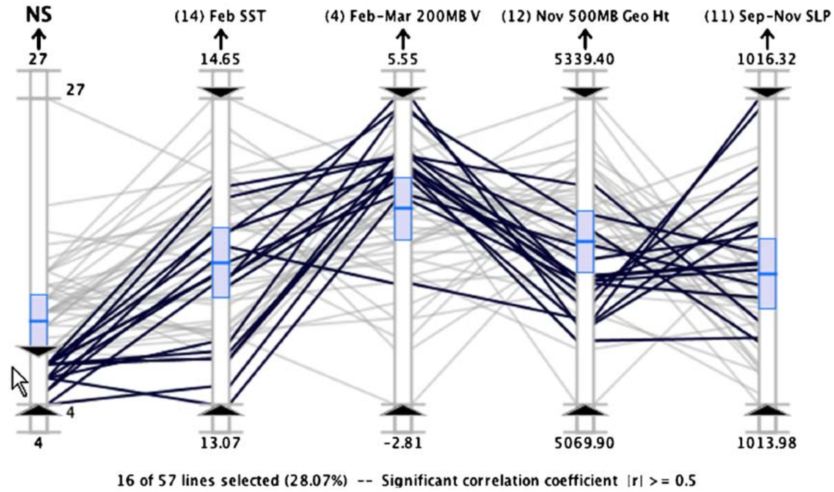

Fig. 7. Variables selected by regression analysis as most influential factors for number of named storms in a season (1950–2006). Below average seasons are highlighted. Tighter clustering of lines for February–March 200-mb South Indian Ocean meridional winds (4) and November North Atlantic 500-mb geopotential heights (12) suggest they are most influential contributors to quiet Atlantic tropical cyclone seasons (web: color, print: black-and-white).

correlates the presence of high pressure in the western U.S. and over the Atlantic, low summer Atlantic SLP, and warm SST as necessary conditions for intense hurricanes.

Because there is unexplained variance and several predictors, can parallel coordinates glean any more information? To answer this question, the data sets are stratified into below normal, normal, and above normal seasons using the software's interactive capabilities, and the significant predictors identified by the stepwise regression are analyzed visually. Using the axis box plots (drawn using the standard deviation and mean), the below normal, normal, and above normal seasons are determined by moving the query sliders for the axis of interest to encapsulate the lines above the standard deviation range, within the standard deviation range, and below the standard deviation range, respectively. After setting the query sliders, the aerial perspective shading highlights the relationships of interest, thus enabling rapid visual analysis of the variables.

Fig. 7 shows a plot for seasons with below normal named storms (sample size of 16). Even though the regression shows February Atlantic SST (14) as the most important overall predictor, it is not as effective for discerning inactive seasons. The plot shows considerable scatter, and with only 6 years of significantly below average SST. The dynamic query capabilities of this parallel coordinates application make these combined queries and subsample analysis an intuitive exercise.

September–November Gulf of Mexico SLP (11) also exhibits much scatter, with a slight majority of years with above normal pressure. However, February–March 200-mb South Indian Ocean meridional winds (4) — a surrogate measurement of El Niño, shows 15 seasons (94%) of strong north winds, tightly clustered in the plots. *This suggests El Niño is the major contributor to inactive Atlantic tropical cyclone seasons.* Note also that below normal November North Atlantic 500-mb geopotential heights (12) plays a pivotal role for quiet seasons. Fourteen seasons (87%) contain lower geopotential heights in November, suggesting the presence of upper-level troughs which can shear tropical cyclones. However, this signal is not as strong as the El Niño predictor. Additionally, many unshaded lines exist for positive 200-mb V, showing that other factors besides El Niño contribute to normal and active seasons. In fact, a similar parallel coordinates stratification analysis shows that November North Atlantic 500-mb geopotential heights (12) and September –November Gulf of Mexico SLP (11) tend to be the critical players for an active tropical cyclone season (not shown).

Fig. 8 shows seasons with below normal hurricane activity (19 seasons). El Niño again tends to dominate the signal through the fall Gulf of Alaska SLP (6) term. However, in contrast to number of named storms, Atlantic SST (16) becomes important for number of hurricanes. This suggests that when water temperature is below normal, tropical storms will have difficulty reaching hurricane status. For above normal hurricane activity (Fig. 9), June–July Atlantic SST (16), November North Atlantic 500-mb geopotential height (12), and Gulf of Mexico SLP (11) tend to exert dominant roles, with El Niño a secondary factor.

Intense hurricanes warrant special consideration, since they cause 80% of the economic damage from tropical cyclones. Fig. 10 shows that cold February Atlantic SSTs (14) and high Atlantic June–July SLP (10) tend to reduce the number of intense hurricanes, with November North Atlantic 500-mb geopotential heights (12) playing a secondary role and September 500-mb geopotential heights in western North America (7) contributing no role. In contrast, all four predictors have tightly clustered lines showing they all play dominant roles in seasons with above normal intense hurricane activity (Fig. 11). These terms are associated with the presence of ridges in the western U.S. and the Atlantic, below average Atlantic SLP, and warm wintertime Atlantic SST off the northwestern European Coast. Ridges are low shear environments, showing that the lack of upper-level troughs is an important factor for seasons with many intense hurricanes. Low SLP indicates minimal subsidence. Sinking air suppresses cloud growth and also dries the lower atmosphere, both of which are not conducive to the formation and development of tropical cyclones. Low SLP also could indicate better organized tropical waves (from which many Atlantic tropical cyclones form). Warm wintertime northeast Atlantic water also is a good precursor for above average intense hurricane activity.

This parallel coordinates application can also investigate the differences between the extremely busy 2005 season and the slightly below average 2006 season. Fig. 12 shows the 2005 and 2006 seasons along with the chosen predictors from all three categories (named storms, hurricanes, and intense hurricanes) listed in Table 3. This plot reveals that most of the terms are nearly the same except for October–November SLP in the Gulf of Alaska (6) (above average in 2005, below average in 2006) and June–July SLP in the tropical Atlantic (10) (below average in 2005, above

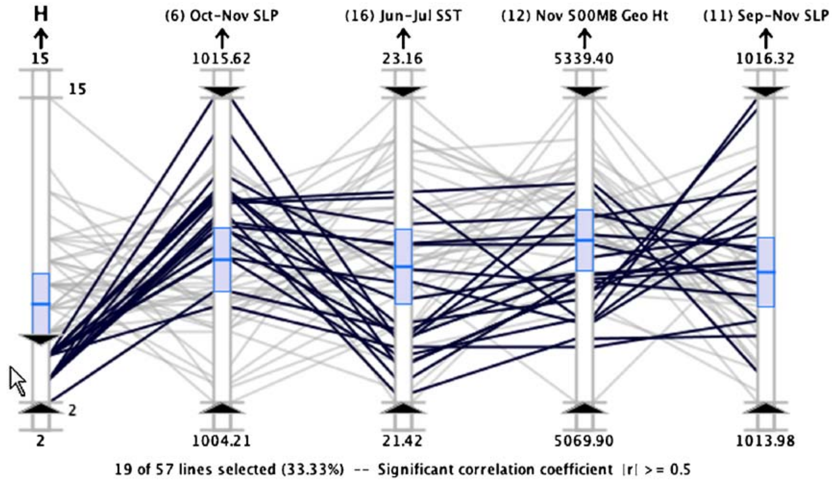

Fig. 8. Variables selected by regression analysis as most influential factors for number of hurricanes in a season (1950–2006). Below average seasons are highlighted. El Niño dominates signal with October–November Gulf of Alaska SLP (6) term, and June–July northeast subtropical Atlantic SST (16) becomes important (web: color, print: black-and-white).

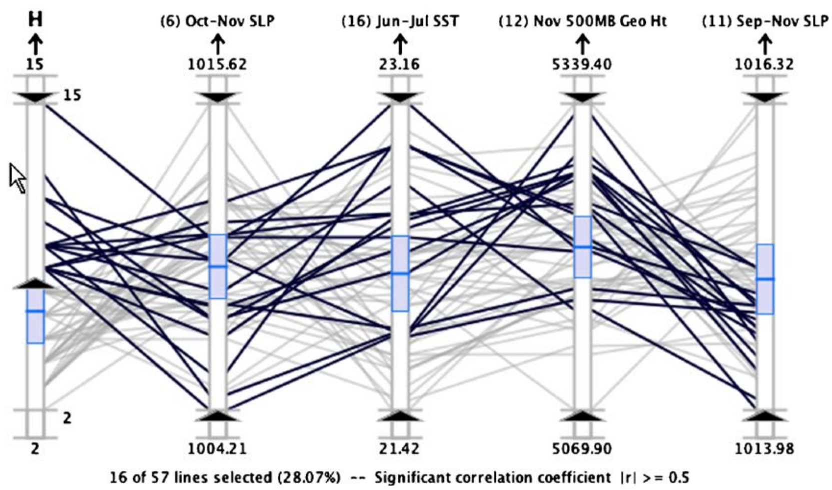

Fig. 9. Variables selected by regression analysis as most influential factors for number of hurricanes in a season (1950–2006). Above average seasons are highlighted. This plot suggests that El Niño term (Gulf of Alaska October–November SLP (6)) is a secondary factor to other three terms (web: color, print: black-and-white).

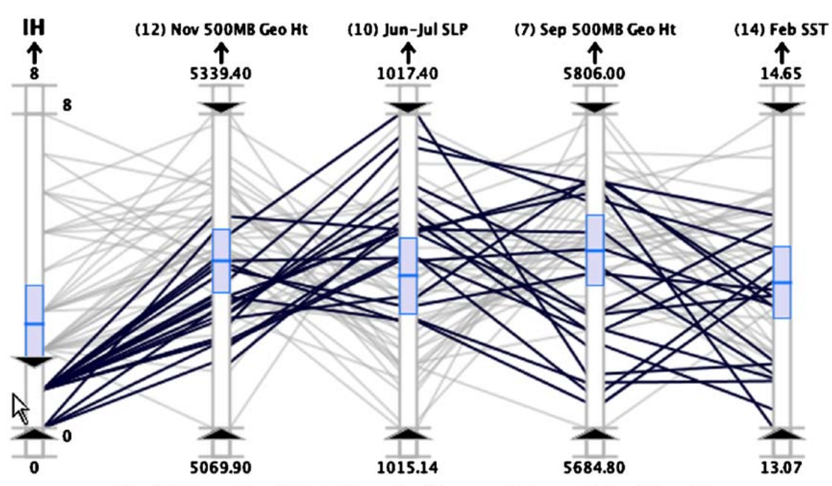

Fig. 10. Variables selected by regression analysis as most influential factors for number of intense hurricanes in a season (1950–2006). Below average seasons are highlighted. Plots shows that cold February coastal Europe SST (14) and high June–July tropical Atlantic SLP (10) tend to reduce number of intense hurricanes. November 500-mb North Atlantic geopotential height (12) also plays a secondary role (web: color, print: black-and-white).

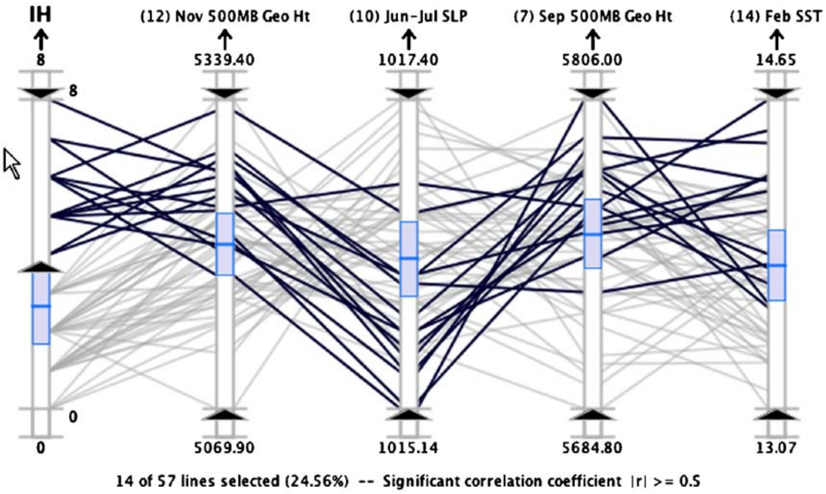

Fig. 11. Variables selected by regression analysis as most influential factors for number of intense hurricanes in a season (1950–2006). Above average seasons are highlighted. All four predictors have tightly clustered lines suggesting they all play dominant roles in seasons with high intense hurricane activity (web: color, print: black-and-white).

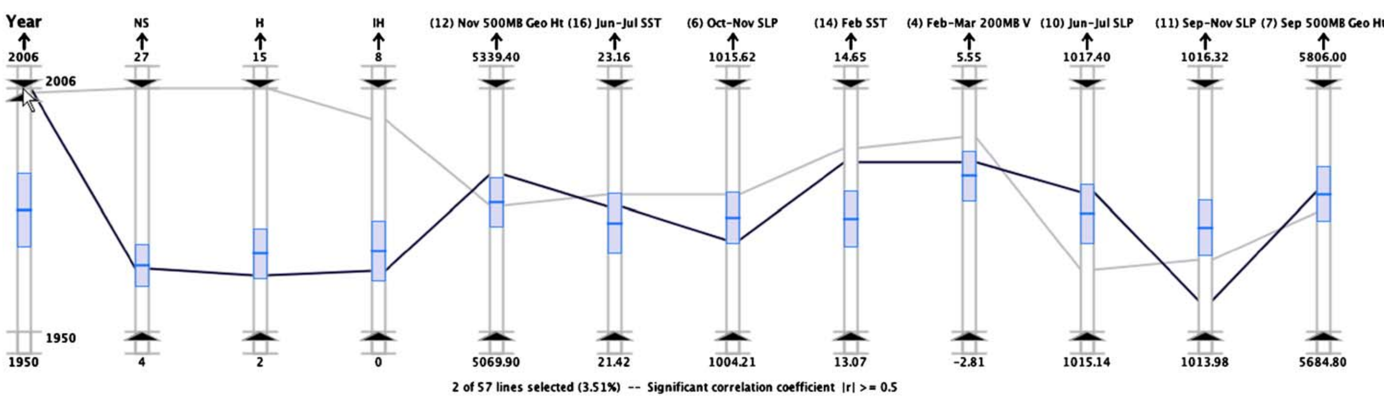

Fig. 12. Variables selected by regression analysis as most influential factors for number of named storms, hurricanes, and intense hurricanes in a season (1950–2006). Two years are queried: 2005 (above average activity) and 2006 (normal to below average activity). Continuous aerial perspective shading is used to highlight 2006 season polyline with a darker shade of gray. October–November Gulf of Alaska SLP (6) and June–July tropical Atlantic SLP (10) exhibit biggest differences (web: color, print: black-and-white).

average in 2006). and Postanalysis of the 2006 Hurricane season by Colorado State University[3] and research by Bell et al. (2007) show that the tropical Atlantic was quite dry through most of the 2006 hurricane season due to subsidence associated with the onset of an unusually late ENSO event (indicated by the Gulf of Alaska SLP), as well as frequent outbreaks of African dust storms that year.

6. Conclusion

This research has shown that a visual analysis system based on interactive parallel coordinates can be used to confirm and clarify the results of stepwise regression in climate analysis. The effectiveness of the system concepts are demonstrated via a real-world case study to identify the most significant predictors for seasonal tropical cyclone statistics. Throughout the development and evaluation of this system, the results have been evaluated by a hurricane expert, Dr. Patrick Fitzpatrick, who is also a co-author of this paper. Based on his feedback, the system facilitates more rapid and open exploratory analysis of climate data than traditional approaches. Unlike the traditional static graphical analysis techniques that are limited to two or three dimensions, the scientists can interactively explore the relationships in this dynamic visualization system that is only restricted by the horizontal display resolution. While stepwise regression provides an ordering of the most significant variables, the visual analysis using the parallel coordinates system provides a deeper understanding of the behavior of environmental predictors for hurricane seasons.

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[3] http://tropical.atmos.colostate.edu/Forecasts/2006/nov2006/

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The Effects of Virtual Reality, Augmented Reality, and Motion Parallax on Egocentric Depth Perception

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Abstract

As the use of virtual and augmented reality applications becomes more common, the need to fully understand how observers perceive spatial relationships grows more critical. One of the key requirements in engineering a practical virtual or augmented reality system is accurately conveying depth and layout. This requirement has frequently been assessed by measuring judgments of egocentric depth. These assessments have shown that observers in virtual reality (VR) perceive virtual space as compressed relative to the real-world, resulting in systematic underestimations of egocentric depth. Previous work has indicated that similar effects may be present in augmented reality (AR) as well.

This paper reports an experiment that directly measured egocentric depth perception in both VR and AR conditions; it is believed to be the first experiment to directly compare these conditions in the same experimental framework. In addition to VR and AR, two control conditions were studied: viewing real-world objects, and viewing real-world objects through a head-mounted display. Finally, the presence and absence of motion parallax was crossed with all conditions. Like many previous studies, this one found that depth perception was underestimated in VR, although the magnitude of the effect was surprisingly low. The most interesting finding was that no underestimation was observed in AR.

CR Categories: I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Virtual Reality; H.5.1 [Information Systems]: Multimedia Information Systems—Artificial, Augmented, and Virtual Realities H.1.2 [Information Systems]: User/Machine Systems—Human Factors

Keywords: depth perception, augmented reality, virtual reality, motion parallax

1 Introduction

Egocentric depth perception has been thoroughly investigated in virtual reality with many studies indicating that the locations of target objects relative to the observer are consistently underestimated [Loomis and Knapp 2003; Livingston et al. 2005; Swan II et al. 2007]. One explanation for this phenomenon is that, in purely virtual environments, observers are not presented with the full gamut of depth cues that are normally available when viewing a real-world scene. Hu et al. [2000] presented observers, in a near-field virtual environment, with varying numbers of depth cues and found a positive correlation between the number of available depth cues and accuracy when placing an object on a virtual surface, lending credence to this theory.

Although depth perception in virtual reality has been well studied, very little work has been done to determine if similar perceptual issues are present in augmented reality. One study conducted by Swan et al. [2007] indicates that similar underestimation effects exist in augmented reality, when viewing a scene through an optical see-through head-mounted display (HMD) from a fixed viewpoint. The experiment described in this paper attempts to replicate the findings reported by Swan et al. [2007], and determine if the addition of motion parallax as a depth cue will aid observers in more accurately perceiving the location of target objects. Another goal is to directly compare depth judgments in virtual and augmented reality. A related contribution of this paper is a novel calibration method that we developed to ensure proper registration of the virtual and real worlds.

2 Experimental Setup and Task

The experiment took place in a hallway where observers viewed a target object placed along the ground plane anywhere from 2 to 8 meters away. The target object was a white, wireframe pyramid measuring 23.5 cm in width and height. An NVIS nVisor ST optical see-through AR HMD was used for this experiment. One of the unique features of this HMD is that it can also serve as a VR HMD by attaching an occluding strip of black plastic with velcro. An InterSense IS-1200 VisTracker was attached to the HMD to provide 6 degree-of-freedom tracking of the observers' head movements. These were attached to a Dell Dimension XPS Gen 4 system. To allow the experimental observers to traverse the required distances, it was necessary to place the equipment on a rolling cart that was pushed behind the observers during the experimental tasks (see Figure 1). As discussed below, the experiment included control conditions to determine if this technique adversely affected the visually directed walking task.

One of the most common techniques used to measure an observer's judgment of egocentric depth is visually directed walking. In this task, observers view a target object for a period of time and then attempt to walk to the object's location without vision. Loomis and Knapp [2003] examined the findings of eight studies that used this technique to judge distances to real-world objects. They found that visually directed walking provided stable judgments of egocentric distance. In addition, they describe the theoretical arguments for why visually directed walking is a good cognitive measure of egocentric depth perception.

A small pilot study was conducted prior to collecting data for this experiment. Pilot observers appeared to be hesitant to walk with their eyes closed in an unfamiliar environment, but seemed to become comfortable after roughly five trials. For this reason, all observers were given five practice trials in a hallway adjacent to the experimental location prior to beginning the experiment. Pilot observers also indicated that light emanating from a corridor that intersected the experimental location disrupted their sense of position. It was important that the observers not be distracted during the visually directed walking task. To prevent interference during this ex-

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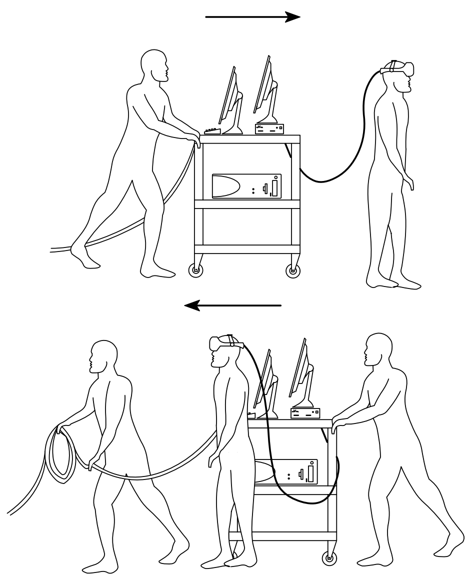

Figure 1: *Cart setup used for moving equipment behind observers both during (top) and after (bottom) visually directed walking tasks.*

periment, the corridor was occluded with a ceiling-suspended sheet that closely approximated the color and texture of the wallpaper in the experimental location. Also, to prevent interference from auditory cues, all observers wore earphones that played white noise throughout the duration of the experiment. Experimenters communicated instructions to the observers through a wireless microphone system that was also connected to the observers' earphones.

3 Variables and Design

Table 1 describes the experimental variables and design.

3.1 Independent Variables

Observers: We recruited 16 observers from a population of university students (undergraduate and graduate), faculty, and staff. 7 of the observers were male, 9 were female; they ranged in age from 19 to 37, with a mean age of 24.4. We screened the observers, via self-reporting, for color blindness and problems with depth perception. All observers volunteered, and were compensated \$10 per hour for their time. Observers spent an average of 2.25 hours completing the experiment.

Viewing Conditions: As shown in Table 1, observers were presented with four viewing conditions: Real, Real+HMD, AR, and VR. In the Real condition, observers saw the real-world target object in the hallway, and did not look through the HMD. When they performed the visually directed walking task, the cart was not pushed behind them. We included this as a control condition, as it duplicates the setup of distance perception studies with real-world target objects [Loomis and Knapp 2003]. In the Real+HMD condition, observers saw the real-world target object in the hallway, but this time regarded the target object through the HMD. We included this as a second control condition, in order to determine if wearing the HMD and having the cart pushed behind the observer interfered with the visually directed walking task. In the VR condition, observers viewed a virtual target object in a completely virtual, photorealistic model of the hallway. This condition replicates many previous VR egocentric depth perception studies [Loomis and Knapp 2003]. Finally, in the AR condition, observers viewed a virtual target object in the real-world hallway. This was the only completely novel viewing condition studied.

Table 1: *Independent and Dependent Variables*

Independent Variables		
observer	16	(random variable)
viewing condition	4	Real Real+HMD AR VR
parallax condition	2	Still (absent) Motion (present)
distance	3	3, 5, 7 meters + 25% noise
repetition	2	1, 2
Dependent Variables		
judged distance	in meters	
normalized error	$\frac{\textit{judged distance}}{\textit{veridical distance}}$	

Parallax Condition: In the Still parallax condition observers were asked to hold their heads still while viewing the target object. This was intended to approximate the viewing conditions described by Swan et al. [2007], where the AR display was rigidly fixed in a stand. In the Motion parallax condition observers were asked to sway back-and-forth while viewing the target object, by shifting their weight from foot to foot. This was done to enable motion parallax as a depth cue.

Distance: For experimental trials, observers saw target objects placed at distances of 3, 5, and 7 meters. Because observers may notice the repetition in such a small set of distances, 25% of the distance judgments were noise trials. For these trials, distances were randomly chosen from 0.25-meter increments in the 2 to 8 meter range. The experimenters recorded the data from the noise trials using the same visually directed walking technique that was used for the experimental trials.

Repetition: Observers saw 2 repetitions of each combination of the other dependent variables.

3.2 Dependent Variables

As shown in Table 1, the primary dependent variable was *judged distance*, which was measured using the visually directed walking task. We also calculated *normalized error = judged distance / veridical distance*. A normalized error near 100% indicates an accurately judged distance; a normalized error $>$ 100% indicates overestimating the distance; and a normalized error $<$ 100% indicates underestimating the distance.

3.3 Experimental Design

We used a factorial nesting of independent variables in this within-subjects experimental design. As shown in Table 1, *viewing condition* varied the slowest; within each condition observers saw each *parallax condition*. The presentation order of *viewing conditions* was controlled by a 4×4 between-subjects Latin Square, while the presentation order of the *parallax conditions* was controlled by a 2×2 between-subjects Latin Square; when combined, these two Latin Squares resulted in a presentation order design that repeated modulo 8 observers. Within each *viewing condition* $\otimes$ *parallax condition* block, our control program generated a list of 3 (*distance*) $\times$ 2 (*repetition*) = 6 experimental distances, and then added 2 random noise distances. The program then randomly permuted the presentation order of the resulting 8 distances, with the restriction that the same distance could not be presented twice in a row. We

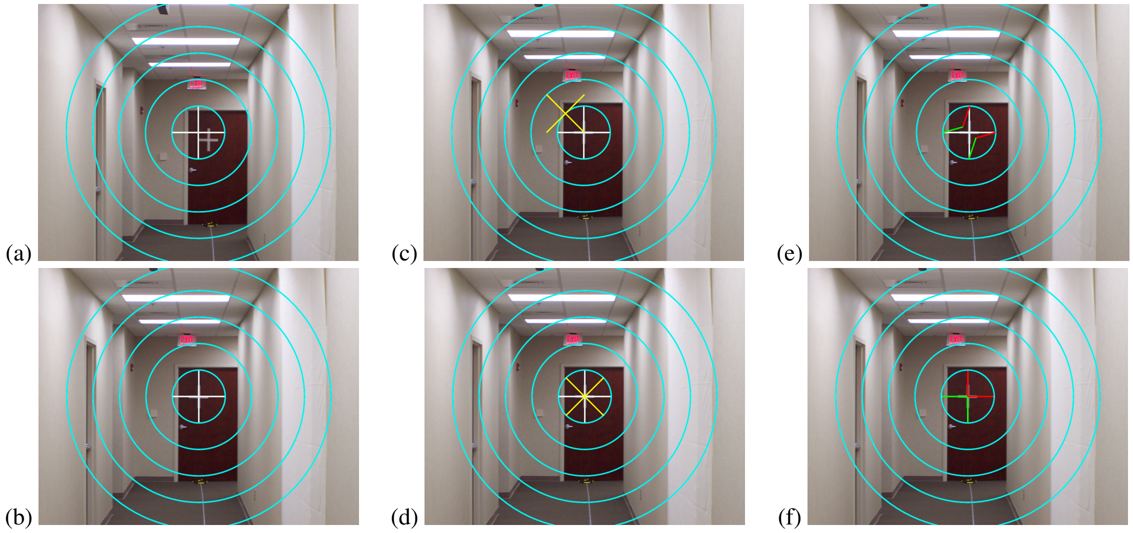

Figure 2: *Calibration procedure as seen by the observers: (a,b) initial virtual/real-world boresighting task, (c,d) translational correction, (e,f) rotational correction. See color plate.*

collected a total of 1024 data points (16 observers $\times$ 4 viewing conditions $\times$ 2 parallax conditions $\times$ (3 distances $\times$ 2 repetitions + 2 noise distances)); 768 of these data points were experimental trials, and 256 were noise trials.

Presentation order effects are a well-known issue for within-subjects designs. Between-subjects designs are immune to order effects, and the majority of VR depth perception experiments have used between-subjects designs. Furthermore, virtual versus real-world presentation order has been found to affect depth perception (e.g., [Ziemer et al. 2006; Plumert et al. 2005]). To mitigate presentation order effects in our within-subjects design, we used the following 4×4 Latin Square:

$$\begin{bmatrix} 1 & 2 & 3 & 4 \\ 2 & 4 & 1 & 3 \\ 3 & 1 & 4 & 2 \\ 4 & 3 & 2 & 1 \end{bmatrix}.$$

In addition to controlling presentation order (condition 1 is presented 1^{st}, 3^{rd}, 2^{nd}, and 4^{th}; likewise for conditions 2, 3, 4), this Latin Square controls the condition that *succeeds* each condition (condition 1 is succeeded by condition 2, condition 3, condition 4, and no condition; likewise for conditions 2, 3, 4), and it also controls the condition that *precedes* each condition (condition 1 is preceeded by no condition, condition 4, condition 3, and condition 2; likewise for conditions 2, 3, 4). These properties exist modulo 4 observers and are maintained modulo 8 observers when the 4×4 square is crossed with a 2×2 square. Therefore, asymmetric transfer effects (such as those described by Plumert et al. [2005]) are counterbalanced by this design.

4 Calibration

The calibration procedure used in this experiment consisted of three steps to correct for (1) optical alignment as well as (2) translational and (3) rotational errors reported by the head tracker.

Optical Alignment and Interpupillary Distance: The first step in the calibration procedure ensures that, for each eye, the observer's optical axis is aligned with the HMD's optical axis. To accomplish this, we implemented the calibration procedure presented by Rolland et al. [1995], who also demonstrate that without this alignment an optical system presents optically incorrect depth cues. The observers were presented with a series of concentric circles that were centered about the optical axis of the display elements (see Figure 2). The HMD has a knob on top of the head which raises and lowers the entire display frame relative to the observer's eyes. The observers were instructed to turn this knob until they could see an equal amount of the upper and lower portions of the outermost circle. The HMD also has knobs that independently shift the left and right display elements horizontally; observers were instructed to turn these knobs until an equal amount of the outermost circle could be seen on the left and right sides of each display. This procedure was performed monocularly for each eye. After these procedures, the optical axis of each of the observers' eyes was both horizontally and vertically aligned with the optical axis of each display element. In addition, each observer's interpupillary distance was measured with a small ruler. The graphics system used this distance when generating stereo imagery.

Translational Tracker Error: As part of developing the experimental apparatus, we carefully calibrated the 6 degree-of-freedom tracker for the hallway. However, because of differences in the way the HMD sits on the head, there are always noticeable translational and rotational errors, even if the display is removed and then replaced on the same observer's head. The goal of the second calibration step was to correct for tracker errors along the observers' x (horizontal) and y (vertical) axis. While similar errors also existed along the z (depth) axis, it was not necessary to correct for them, because the experimental task was always conducted at the same z location for each observer. For this calibration step, the observers were shown a virtual crosshair and a real-world cross placed at their eye height at the end of the hallway (Figure 2a). The observers were then asked to align the two crosshairs by moving their heads (Figure 2b). Once the observers had aligned the crosshairs, their line of sight was parallel to the floor. They were next handed a game controller and shown a virtual, yellow "X" that was translationally controlled by the head tracker (Figure 2c, which shows a typical degree of translational error). The initial position of the X represented the location where the real-world crosshair should be located according to the tracker. The observers then used the game controller to adjust the position of the X until it was aligned with both the real and virtual crosshairs (Figure 2d). This adjustment added a translational offset to the values reported by the head tracker, which translationally corrected for the way the HMD was

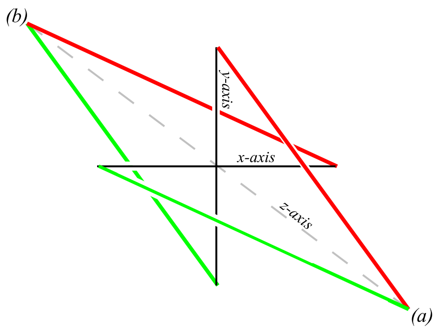

Figure 3: *Side view of the 3D Compass. Observers looked along the z-axis, from point (a) to point (b). See color plate.*

sitting on their head.

Rotational Tracker Error: The goal of the third calibration step was to correct for rotational tracker errors around the observers' pitch (up/down) and yaw (side/side) axis. The tracker also had roll (twist) errors, but these errors were not important for this task. The observers were shown the same real and virtual crosshairs as in the previous step and asked to perform the same boresighting task (Figure 2b). This time the observers were shown a 3-dimensional crosshair that we called the 3D Compass (see Figure 3). The 3D Compass is rotationally controlled by the head tracker, but it is translationally centered at the virtual crosshair. The shape of the 3D Compass is such that if there is any rotational offset when aligned with the real world crosshair, its 2D projection results in an accidental view with a star-like shape (Figure 2e, which shows a typical degree of rotational error). However, when all rotational errors have been compensated, the 2D projection results in another accidental view that looks like a plus sign (Figure 2f). The observers were given a game controller and asked to adjust the shape until it became a plus. This adjustment added a pitch and yaw offset to the values reported by the head tracker. The 3D Compass is sensitive and easy to use; we believe it is a novel contribution to AR calibration techniques.

Together, these calibration procedures resulted in accurate registration between the virtual and real worlds. Observers were required to perform this calibration before every block of trials in the AR and VR viewing conditions. Also, if the observers touched, moved, or otherwise jostled the HMD at any point during the trials, the calibration procedure was repeated before any further data was collected.

5 Results

We analyzed *judged distance* results from $N = 768$ data points. A histogram revealed a normal distribution with two outlying values, which were likely data entry errors. These were replaced with the mean of the remaining values in the experimental cell [Barnett and Lewis 1994]. As is typical with distance perception, we found that variability increased with increasing distance (e.g., observers were following Weber's law [Sekuler and Blake 2001]; see Figures 4 and 6). Because of this, the judged distance results do not meet the homogeneity of variance requirement for ANOVA analysis. However, an examination of the *normalized error* results with a histogram showed a normal distribution with homogeneous variability over all independent variables, including distance. Because of this, and because it is normalized with respect to distance, and because it increased experimental power, for normalized error we analyzed all $N = 1024$ data points (both the experimental and the noise trials). All ANOVA analysis was conducted with normalized error.

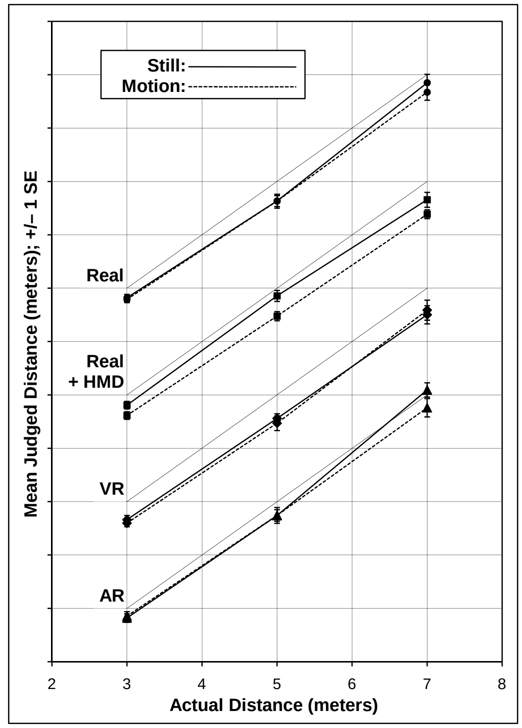

Figure 4: *Depth judgments over all observers* $(N = 768)$. *The diagonal lines are veridical; the results are offset by viewing condition for clarity. For this and subsequent graphs, absent error bars indicate an error interval that is smaller than the mean symbol.*

Figure 4 shows the main results as judged distance versus actual distance; for clarity these are offset and grouped by environment. In the Real condition, observers underestimated the distance slightly (*normalized error* = 94.1%; $N = 1024$), but their performance did not interact with either parallax or distance. Observers performed similarly in the AR condition (96.0%). In the VR condition, observers showed an underestimation effect (91.1%), which is significantly different than 100% $(F(1, 15) = 13.10, p = .003, N = 256)$ but is small by historical standards (see Figure 7). The difference between the AR and VR environments was also significant $(F(1, 15) = 5.86, p = .029, N = 512)$.

The only effect of motion parallax occurred for the Real+HMD environment, which showed a significant difference between the Still (94.6%) and Motion (89.6%) conditions $(F(1, 15) = 5.29, p = .036, N = 256)$. This effect is somewhat consistent with Willemsen et al. [2004], who found that the mass and inertia of an HMD caused depth underestimation. In this case, we could expect that the Motion condition would make HMD mass and inertia effects more pronounced.

Figure 5 shows the normalized error per observer. Note that observers 1, 6, and 13 underestimated to a much greater degree than the rest of the observers. This suggests splitting the observers into two groups, an underestimating group consisting of observers 1, 6, and 13, and a group with the remaining observers. Of the 1024 normalized error observations, a discriminate analysis with this model correctly places 77.0% of the observations into the proper group, and a regression on this model accounts for $r^2 = 23.2\%$ of the observed variance.

Figure 6 shows the results for the remaining 13 observers when these 3 underestimating observers are removed. Here the same results as above are observed, but the degree of underestimation is considerably reduced. Observers performed veridically in both the

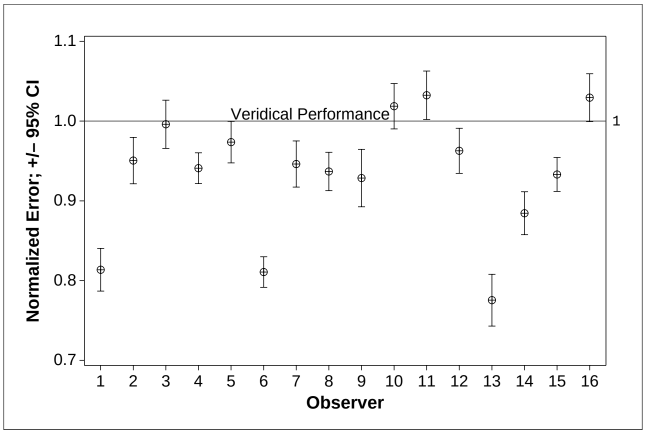

Figure 5: *The normalized error per observer* $(N = 1024)$. *Note the underestimation of observers 1, 6, and 13.*

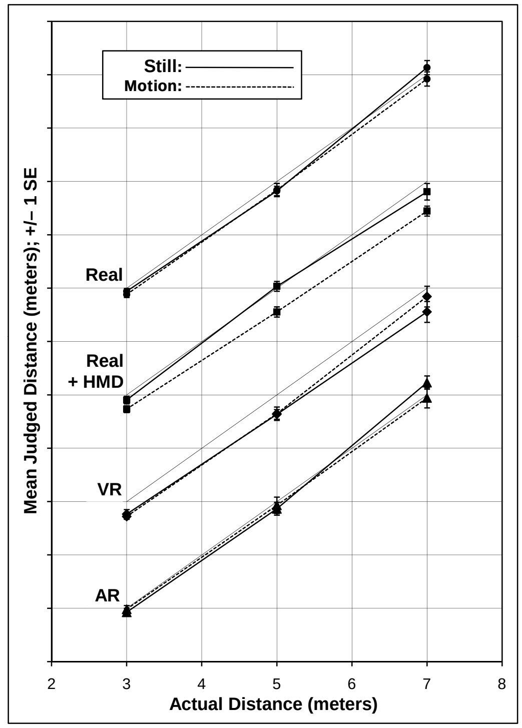

Figure 6: *Depth judgments with underestimating observers removed* $(N = 624)$*; see Figure 5.*

Real (97.9%; $N = 832$ including noise trials) and AR (98.9%) environments. Observers underestimated in the VR environment (94.1%), which is still significantly different than 100% although the sample size is smaller $(F(1, 12) = 6.79, p = .023, N = 208)$. There is trend of significance between the AR and VR environments $(F(1, 12) = 4.08, p = .066, N = 416)$, which becomes significant if we exclude the noise trials $(F(1, 12) = 6.32, p = .027, N = 312)$. And for the Real+HMD environment, a significant difference remains between the Still (97.8%) and Motion (91.5%) conditions $(F(1, 12) = 5.92, p = .032, N = 208)$.

6 Discussion and Conclusions

Table 2 and Figure 7 show the normalized error from a number of recent egocentric depth perception experiments that investigated AR, VR, real-world environments, and real-world environments seen through an HMD. There are several interesting findings in this table and graph. First, the overall trend of egocentric depth underestimation in VR environments, relative to other environments, is clear. Second, Figure 7 provides a context for the magnitude of the underestimation observed in the current study. The amount of underestimation for the Real condition agrees well with previous studies. The amount of underestimation for the VR environment is low compared to most previous studies, and the amount of underestimation for the AR environment is also low compared to the small number of previous studies. A likely reason for the relatively small amount of observed VR underestimation is the ability of the nVis nVisor display to be calibrated in AR mode, and then used in VR mode. Because the real world is visible in AR, critical scene parameters, such as field of view and position and orientation tracker corrections, can be set relative to real-world, ground truth referent objects. This degree of calibration accuracy is not possible in pure VR displays.

We expected motion parallax to make depth judgments more accurate, because motion parallax adds to the depth cues that are available in the scene. Contrary to our expectations, motion parallax did not make depth judgments more accurate; its only effect was an interaction with environment—it made depth judgments less accurate (more underestimated) in the Real+HMD environment. This can be compared to the findings of Williamsen et al. [2004], who found underestimation in a Real+HMD environment compared to a Real environment when viewing objects without motion parallax. However, we only found underestimation in the Real+HMD environment in the motion parallax condition; we found no parallax effects in the VR or AR environments, where observers were also wearing the HMD. And, although Beall et al. [1995] found that motion parallax has a very week effect on an observer's perception of depth, we found a significant motion parallax effect in the Real+HMD environment.

Our most interesting experimental result was the lack of underestimation in AR compared with VR. To the best of our knowledge, this is the first experiment to directly compare egocentric depth perception in AR and VR using the same experimental framework. A number of hypothesized reasons for the VR underestimation effect have been studied [Swan II et al. 2007]; these include the HMD's limited field of view, the weight and inertia of the HMD, monocular versus stereo viewing, the quality of the rendered graphics, knowledge that the virtual scene represents an actual real-world location, and the effect of practice with feedback. To date, although some of these reasons have been found to contribute to VR underestimation, none of them fully describe it. In this experiment we have added to this body of knowledge by demonstrating that the effect disappears when observers view virtual objects against an actual, real-world scene. We have also demonstrated that observers can make accurate egocentric depth judgments in AR, when measured using the same directed walking techniques that have been widely studied in VR.

Acknowledgments

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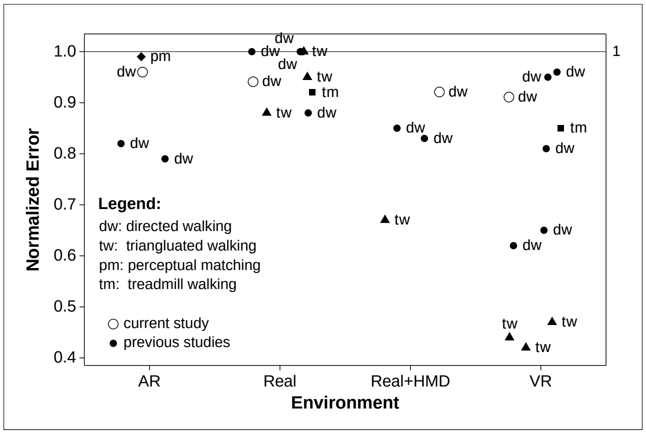

Figure 7: *The normalized egocentric depth perception error from the current study ($N = 1024$), in the context of many reported studies. This graph visualizes the information in Table 2.*

Table 2: *Normalized Error (NE) results from a variety of recent studies, with distances in meters. This information is visually depicted in Figure 7.*

STUDY	DISTANCES	NE	PROTOCOL
AUGMENTED REALITY			
Current Study	3.0 – 7.0	96%	Direct Walking
[Swan II et al. 2006]	5.25 – 44.31	99%	Perceptual Matching
[Swan II et al. 2007] (AR)	3.0 – 7.0	79%	Direct Walking
[Swan II et al. 2007] (AR+Real)	3.0 – 7.0	82%	Direct Walking
REAL WORLD			
Current Study	3.0 – 7.0	94%	Direct Walking
[Interrante et al. 2006]	3.0 – 9.2	100%	Direct Walking
[Knapp 1999]	5.0 – 15.0	100%	Triangulated Walking
[Swan II et al. 2007]	3.0 – 7.0	88%	Direct Walking
[Thompson et al. 2004]	5.0 – 15.0	95%	Triangulated Walking
[Willemsen and Gooch 2002]	2.0 – 5.0	100%	Direct Walking
[Willemsen et al. 2004]	4.0 – 8.0	100%	Direct Walking
[Willemsen et al. 2004]	4.0 – 8.0	88%	Triangulated Walking
[Witmer and Sadowski 1998]	4.6 – 32.0	92%	Treadmill Walking
REAL WORLD SEEN THROUGH HMD			
Current Study	3.0 – 7.0	92%	Direct Walking
[Swan II et al. 2007]	3.0 – 7.0	83%	Direct Walking
[Willemsen et al. 2004]	4.0 – 8.0	85%	Direct Walking
[Willemsen et al. 2004]	4.0 – 8.0	67%	Triangulated Walking
VIRTUAL REALITY			
Current Study	3.0 – 7.0	90%	Direct Walking
[Interrante et al. 2006] (Base)	3.0 – 9.2	95%	Direct Walking
[Interrante et al. 2006] (Post)	3.0 – 9.2	96%	Direct Walking
[Durgin et al. 2002]	2.0 – 8.0	65%	Direct Walking
[Knapp 1999]	5.0 – 15.0	42%	Triangulated Walking
[Thompson et al. 2004]	5.0 – 15.0	44%	Triangulated Walking
[Willemsen and Gooch 2002]	2.0 – 5.0	81%	Direct Walking
[Willemsen et al. 2004]	4.0 – 8.0	62%	Direct Walking
[Willemsen et al. 2004]	4.0 – 8.0	47%	Triangulated Walking
[Witmer and Sadowski 1998]	4.6 – 32.0	85%	Treadmill Walking

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Usability Engineering for Augmented Reality: Employing User-Based Studies to Inform Design

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Abstract—A major challenge, and thus opportunity, in the field of human-computer interaction and specifically usability engineering (UE) is designing effective user interfaces for emerging technologies that have no established design guidelines or interaction metaphors or introduce completely new ways for users to perceive and interact with technology and the world around them. Clearly, augmented reality (AR) is one such emerging technology. We propose a UE approach that employs user-based studies to inform design by iteratively inserting a series of user-based studies into a traditional usability-engineering life cycle to better inform initial user interface designs. We present an exemplar user-based study conducted to gain insight into how users perceive text in outdoor AR settings and to derive implications for design in outdoor AR. We also describe "lessons learned" from our experiences, conducting user-based studies as part of the design process.

Index Terms—User interfaces, ergonomics, evaluation/methodology, screen design, style guides, multimedia information systems, artificial, augmented, virtual realities.

1 Introduction and Context

A major challenge and, thus, opportunity, in the field of human-computer interaction (HCI) and specifically usability engineering (UE) is designing effective user interfaces for emerging technologies that have no established design guidelines or interaction metaphors, or introduce completely new ways for users to perceive and interact with technology and the world around them. Clearly, augmented reality (AR) is one such emerging technology. In these design contexts, it is often the case that user-based studies, or traditional human factors studies, can provide valuable insight. However, a literature survey we conducted in 2004 [1] found that user-based studies have been underutilized in AR, and we posit that this underutilization extends well beyond this specific technology. Our survey found that, in a total of 1,104 articles on AR, only 38 ($\sim$ 3 percent) addressed some aspect of HCI, and only 21 ($\sim$ 2 percent) described a formal user-based study. As a community, how can we expect to design and deploy effective application-level user interfaces and interaction techniques when we have too little understanding of human performance in these environments? We assert that the most effective user interfaces for emerging technologies will be grounded on user-based studies that aim to understand fundamental perceptual and cognitive factors, especially for those technologies that fundamentally alter the way humans perceive the world (for example, VR, AR, etc.).

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In this paper, we propose a UE approach that employs user-based studies to inform design by iteratively inserting a series of user-based studies into a traditional UE life cycle to better inform initial user interface designs. Under this approach, user performance can be explored against combinations of design parameters (that is, experimental factors and levels) to discover what combinations of parameters support the best user performance under various conditions. What makes this approach different than traditional HCI approaches is that basic user interface and/or interact issues are explored vis-à-vis user-based studies *as part of* the UE of a specific application, as opposed to application developers drawing from a body of established guidelines produced in the past by others performing low-level, or generic, user-based studies.

We have applied this approach as part of the UE and software development of the BARS. Following a domain analysis [3], we began to identify more than 20 scientific challenges, over half of which were user interface design challenges that required insight from conducting user-based studies. Since that time, most of our user-based studies have focused on three of these areas: 1) the representation of occlusion [4], 2) understanding depth perception in optical see-through AR [5], [6], and 3) text legibility in outdoor optical see-through AR [7], [8], [9].

We first present our UE approach and justify the importance of employing user-based studies to inform design. We then present an exemplar user-based study, which we conducted to gain insight into how users perceive text in outdoor AR settings and to derive implications for design in outdoor AR.[1] Last, we describe some "lessons learned" from our experiences conducting user-based studies as part of the design process.

1. This study has been previously described by Gabbard et al. [9].

2 UE Approaches to Designing User Interfaces

To date, numerous approaches to software and user interface design have been developed and applied. The waterfall model, developed by Royce [10], was the first widely known approach to software engineering. This model takes a top-down approach based on functional decomposition. Royce admitted that while this process was designed to support large software development efforts, it was inherently flawed since it did not support iteration; a property that he eventually added it to the model.

The spiral model [11] was the first widely recognized approach that utilized and promoted iteration. It is useful for designing user interfaces (as well as software), because it allows the details of user interfaces to emerge over time with iterative feedback from evaluation sessions feeding design and redesign. As with UE approaches, the spiral model first creates a set of user-centered requirements through a suite of traditional domain analysis activities (for example, structured interviews, participatory design, etc.). Following requirements analysis, the second step simply states that a "preliminary design is created for the new system."

Hix and Hartson [12] describe a star life cycle that is explicitly designed to support the creation of user interfaces. The points of the star represent typical design/development activities such as "user analyses," "requirements/usability specifications," "rapid prototyping," etc., with each activity connected through a single center "usability evaluation" activity. The points of the start are not ordered, so one can start at any point in the process but can only proceed to another point via usability evaluation. The design activities focus on moving from a conceptual design to a detailed design.

Mayhew [13] describes a UE life cycle that is iterative and centered on integrating users throughout the entire development process. With respect to design, the UE life cycle relies on screen design standards, which are iteratively evaluated and updated. Both the screen design standards and the detailed user interface designs rely on style guides that can take the form of a "platform" style guide (for example, Mac, Windows, etc.), "corporate" style guide (applying a corporate "look and feel"), "product family" style guide (for example, MS Office Suite), etc.

Gabbard et al. [14] present a cost-effective structured iterative methodology for user-centered design and evaluation of virtual environment (VE) user interfaces and interaction. Fig. 1 depicts the general methodology, which is based on sequentially performing:

1. user task analysis,
2. expert guidelines-based evaluation,
3. formative user-centered evaluation, and
4. summative comparative evaluations.

While similar methodologies have been applied to traditional (GUI-based) computer systems, this methodology is novel because we specifically designed it for—and applied it to—VEs, and it leverages a set of heuristic guidelines specific to VEs. These sets of heuristic guidelines were derived from Gabbard's taxonomy of usability characteristics for VEs [15].

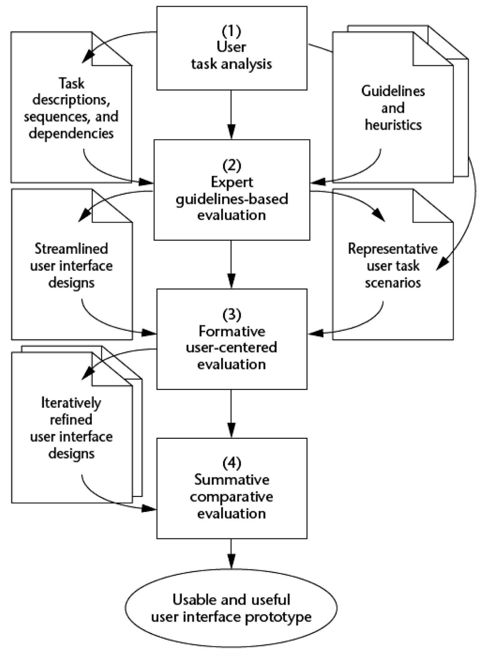

Fig. 1. The user-centered design and evaluation methodology for VE user interaction described by Gabbard et al. [14].

A shortcoming of this approach is that it does not give much guidance for design activities. The approach does not describe how to engage in design activities but, instead, asserts that initial designs can be created using input from task descriptions, sequences, and dependencies, as well as guidelines and heuristics from the field. Since this methodology assumes the presence of guidelines and heuristics to aid in designs to be evaluated during the "expert guidelines-based evaluation" phase, it is not applicable to emerging technologies such as AR, where user interface design guidelines and heuristics have not yet been established.

When examining many of the approaches described above—and specifically, the design and evaluation activities—in most cases, design activities rely on leveraging existing metaphors, style guides, or standards in the field (for example, drop down menus, a browser's "back" button, etc.). However, in cases where an application falls within an emerging technological field, designers often have no existing metaphors or style guides, much less standards on which to base their design. Moreover, in cases where the technology provides novel approaches to user interaction or fundamentally alters the way users perceive the interaction space (that is, where technology and the real-world come together), designers often have little understanding of the perceptual or cognitive ramifications of "best guess" designs.

As a result, a process is needed to help designers of novel user interfaces iteratively create and evaluate designs to gain a better understanding of effective design parameters and to determine under what conditions these parameters are best applied. Without this process, applications developed using traditional UE approaches can only improve incrementally from initial designs—which again, are often

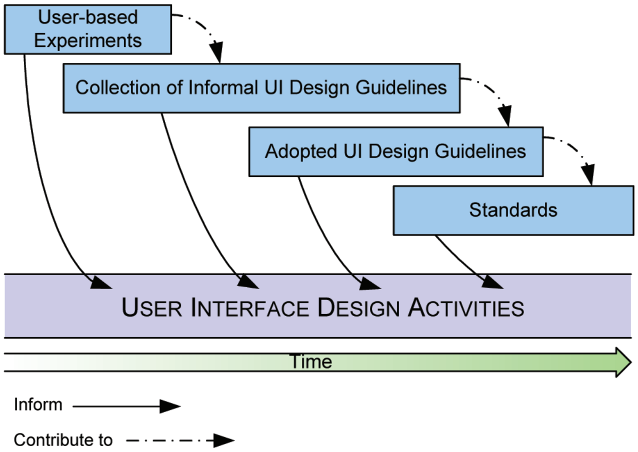

Fig. 2. User-based experiments are a critical vehicle for discovery and usability early in an emerging field's development. Over time, contributions from the field emerge, leading eventually to adopted user interface design guidelines and standards.

based on the developers' best guesses, given the absences of guidelines, metaphors, and standards.

2.1 User Interface Design Activities for AR and Other Emerging Technologies

As shown in Fig. 2, it can be argued that user-based experiments are critical for driving design activities, usability, and discovery early in an emerging technology's development (such as AR). As a technological field evolves, lessons learned from conducting user-based studies are not only critical for the usability of a particular application but provide value to the field as a whole in terms of insight into a part of the user interface design space (for example, of occlusion or text legibility). As time progresses, contributions to the field (from many researchers) begin to form a collection of informal design guidelines and metaphors from which researchers and application designers alike can draw. Eventually, the informal design guidelines are shaken down into a collection of tried-and-true guidelines and metaphors that are adopted by the community. Finally, the guidelines and metaphors become defacto standards or at best deemed "standards" by appropriate panels and committees.

The context of the work reported here, however, falls within the application of user-based studies to inform user interface design; the left uppermost box in Fig. 2. Based on our experiences performing UE and, specifically, the design and evaluation activities for the BARS, we propose an updated approach to user interface design activities for AR systems. This approach emphasizes iterative design activities in between the *user task analysis phase*, where requirements are gathered and user tasks understood, and the *formative user-centered evaluation phase*, where an application-level user interface prototype has been developed and is under examine. With this approach, we couple the expert evaluation and user-based studies to assist in the user interface design activity (Fig. 3). These user-based studies differ from traditional approaches to application design, in that their scope addresses basic user interface or interaction design in lieu of established design guidelines. Expert

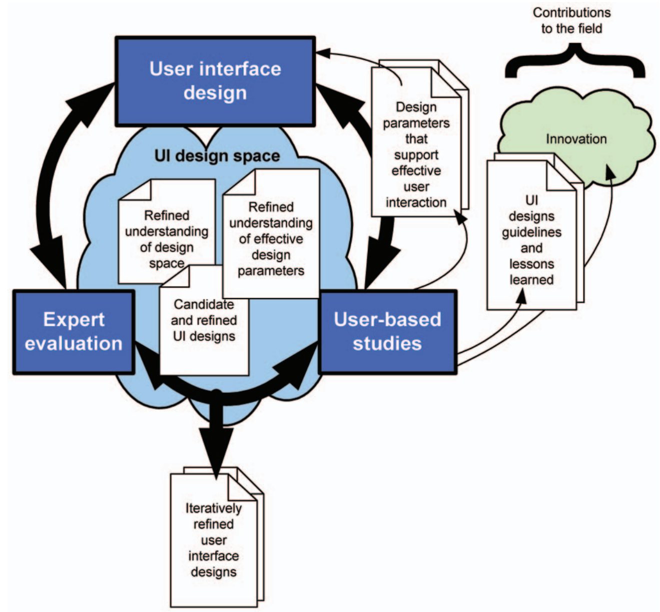

Fig. 3. We applied the depicted user-centered design activities as part of our overall UE approach. With this methodology, expert evaluations along with user-based studies are iteratively applied to refine the user interface design space. It is the scope of the user-based studies that make this approach unique in that that the user-based studies address basic user interface and interaction issues (as opposed to application-level user interface issues) in lieu of established design guidelines.

evaluations can be iteratively combined with well-designed user-based studies to refine the designers' understanding of the design space, understanding of effective design parameters (for example, to identify subsequent user-based studies) and, most importantly, to refine user interface designs. A strength of this approach is that interface design activities are driven by a number of activities; inputs from the user task analysis phase, user interface design parameters correlated with good user interface performance (derived from user-based studies), and expert evaluation results.

Of the three main activities shown in Fig. 3, there are two logical starting points: *user interface design* and *user-based studies*. An advantage of starting with user interface design activities is that designers can start exploring the design space prior to investing time in system development and, moreover, can explore a number of candidate designs quickly and easily. In the past, we have successfully used PowerPoint mockups to examine dozens of AR design alternatives. If mocked up correctly, the static designs can be presented through an optical see-through display, which allows designers to get an idea of how the designs may be perceived when viewed through an AR display in a representative context (for example, indoors versus outdoors).

Once a set of designs has been created, expert evaluations can be applied to assess the static user interface designs, culling user interface designs that are likely to be less effective than others. The expert evaluations are also useful in terms of further understanding the design space by identifying potential user-based experimental factors and levels. Once identified, user-based studies can be conducted to further examine those factors and levels to determine, for example, if the findings of the expert evaluation match that of user-based studies.

In cases where the design space is somewhat understood and designers have specific questions about how different design parameters might support user task performance, designers may be able to conduct a user-based study as a starting point. Under this approach, designers start with experimental design parameters as opposed to specific user interface designs. As shown in Fig. 3, user-based studies not only identify user interface design parameters to assist in UI design but also have the potential to produce UI design guidelines and lessons learned, as well as generate innovation, which provides both tangible contributions to the field while also improving the usability of a specific application.

Ultimately, a set of iteratively refined user interface designs are produced, which are the basis for the overall application user interface. This design can then be evaluated using formative user-centered evaluation, as described by Gabbard et al. [14].

3 Case Study: A User-Based Study Examining Text Legibility in Outdoor AR

In this section, we describe, as a case study, a user-based experiment that seeks to better our understanding of how users perceive text in outdoor AR settings. Note that this study was first reported at VR 2007 [9]. However, this case study extends the VR 2007 work by including an analysis of pairwise contrast comparisons, as described below.

This study is one of many user-based studies that we have conducted as part of our BARS design activities. As depicted in Fig. 3, these this user-based study was part of the proposed iterative design cycle, which included the expert evaluation of PowerPoint mockups, as well as a prior user-based study on text legibility (first reported in [7]). From these experiences, as well as insights from the graphics art field, we identified a number of important design parameters used to drive the design of this study.

3.1 Outdoor Augmented Information

Presenting legible augmenting information in the outdoors is problematic, due mostly to uncontrollable environmental conditions such as large-scale fluctuations in natural lighting and the various types of backgrounds on which the augmenting information is overlaid. There are often cases where the color and/or brightness of a real-world background visually and perceptually conflicts with the color and/or contrast of graphical user interface (GUI) elements such as text, resulting in poor or nearly impossible legibility. This issue is particularly true when using optical see-through display hardware.

Several recent studies in AR have begun to experimentally confirm that which was anecdotally known among outdoor AR practitioners but not yet documented—namely, that text legibility is significantly affected by environmental conditions such as color and texture of the background environment, as well as natural illuminance at both the user's and background's position [8], [7], [16], [17], [18].

One strategy to mitigate this problem is for visual AR representations to actively adapt, in real time, to varying conditions of the outdoor environment. Following this premise, we created a working testbed to investigate interactions among real-world backgrounds, outdoor lighting, and visual perception of augmenting text. We have termed this testbed a "visually active AR testbed." This testbed senses the condition of the environment using a real-time video camera and lightmeter. Based on these inputs, we apply active algorithms to GUI text strings, which alter their visual presentation and create greater contrast between the text and the real-world backgrounds, ultimately supporting better legibility and thus user performance. This concept easily generalizes beyond text strings to general GUI elements.

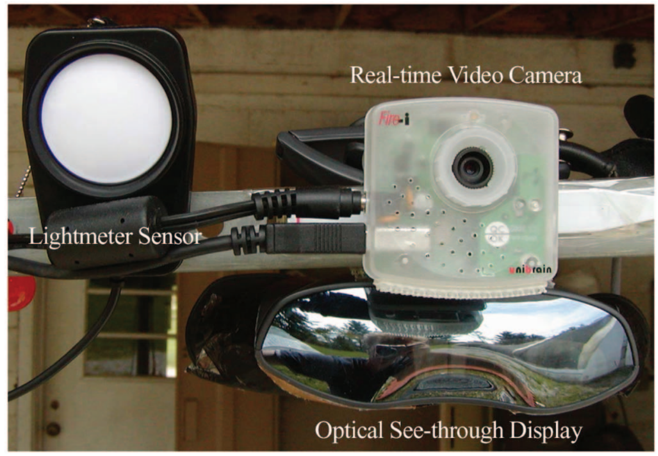

Fig. 4. AR display, video camera, and lightmeter components of our visually active AR testbed.

We conducted a study that examined the effects on user performance of outdoor background textures, text colors, text drawing styles, and text drawing style algorithms for a text identification task. We captured user error, user response time, and details about text drawing and real-world background colors for each trial.

3.2 A Visually Active AR Testbed

Our recent instantiation of a visually active AR user interface serves as a testbed for empirically studying different text drawing styles and active text drawing algorithms under a wide range of outdoor background and illuminance conditions. Fig. 4 shows our testbed, which employs a real-time video camera to capture a user's visual field of view and to specifically sample the portion of the real-world background on which a specific user interface element (for example, text) is overlaid. It also employs a real-time lightmeter (connected via RS232) to provide a real-time natural illuminance information to the active system. The user study reported in this paper only actively uses the camera information; the testbed recorded lightmeter information but did not use it to drive the active algorithms. We anticipate developing algorithms that are actively driven by the lightmeter in the future.

As shown in Fig. 4, the AR display, camera, and lightmeter sensor are mounted on a rig, which in turn is mounted on a tripod (not shown in the figure). Participants sat in an adjustable-height chair so that head positions are consistent across all participants. Our testbed did not use a motion tracking system. For this study, we fixed the participants' field-of-view on different backgrounds by repositioning the rig between background conditions. We used previously captured camera images of backgrounds to assist in the positioning procedure and to ensure that each participant's FOV is the same for each background.

Our testbed uses the text's screen location and font characteristics to compute a screen-aligned bounding box for each text string. It then computes the average color of this bounding box and uses this color to drive the active text drawing algorithms—which in turn determine a text drawing style color. For example, if using a billboard drawing style (see Fig. 7), the active text drawing algorithm uses the sampled background color as an input to determine what color to draw the billboard. The specific text drawing styles and text drawing style algorithms are discussed in more detail below.

Our testbed was implemented as a component of the BARS and uses an optical see-through display, a real-time video camera, a lightmeter, and a mobile laptop computer equipped with a 3D graphics card. The optical see-through display was a Sony Glasstron LDI-100B biocular optical see-through display, with SVGA resolution and a 28-degree horizontal field of view in each eye. We used a UniBrain Fire-i firewire camera (with settings of YUV 4:2:2 format, 640×480 resolution, 30Hz, and automatic gain control and exposure timing). The lightmeter is an Extech 407026 Heavy Duty Light Meter with RS232 interface to measure illuminance at the user's position. Our laptop system (and image generator) was a Pentium M 1.7-GHz computer with 2 Gbytes of RAM and an Nvidia GeForce4 4200 Go graphics card generating monoscopic images, running under Windows 2000. We used this same computer to collect user data. Fig. 4 shows the HMD, camera, and lightmeter components.

3.3 Task and Experimental Setup

We designed a task that abstracted the kind of short reading tasks such as reading labels, which are prevalent in many proposed AR applications. For this study, we purposefully designed the experimental task to be a low-level visual identification task. That is, we were not concerned with participants' semantic interpretation of the data but simply whether or not they could quickly and accurately read information. Moreover, the experimental task was designed to force participants to carefully discern a series of random letters so that task performance was based strictly on legibility. The task was a relatively low-level cognitive task consisting of visual perception of characters, scanning, recognition, memory, decision making, and motor response.

As shown in Fig. 5, participants viewed random letters arranged in two different blocks. The upper block consisted of three strings of alternating upper- and lowercase letters, while the lower block consisted of three strings of uppercase letters. We instructed the participant to first locate a target letter from the upper block; this was a pair of identical letters, one of which was an uppercase and the other lowercase (for example, "Vv" in Fig. 5). Placement of the target letter pair in the upper block was randomized, which forced participants to carefully scan through the block. We considered several other visual cues such as underlining, larger font size, and bold text for designating the target letter; however, we realized that this would result in a "pop-out" phenomenon wherein the participant would locate the target without scanning the distracting letters.

Fig. 5. Our experimental task required participants to identify the pair of identical letters in the upper block (for example, "Vv") and respond by pressing the numeric key that corresponds to the number of times that letter appears in the lower block (for example, "2"). Note that this image is a screen capture (via camera) of the participants' field of view and overlaid text and is not an exact representation of what the participants viewed through the AR display.

We used the restricted alphabet "C, K, M, O, P, S, U, V, W, X, Z" to minimize variations in task time due to the varying difficulty associated with identifying two identical letters whose upper- and lowercase appearance may or may not be similar. A posthoc analysis showed an effect size of $d = .07$ error for letter, which is small when compared to the other effect sizes reported in this paper.

After locating the target letter, the participant was then instructed to look at the lower block and count the number of times the target letter appeared in the lower block. The placement of the target letters in the lower block was randomized. Participants were instructed that the target letter would appear 1, 2, or 3 times. The participant responded by pressing the "1," "2," or "3" key to indicate the number of times the target letter appeared in the lower block. In addition, participants were instructed to press the "0" key if they found the text completely illegible.

To minimize carryover effects of fatigue, a rest break was also provided every 28 trials; participants were instructed to close their eyes and relax. The length of the rest break was determined by each participant. After each rest break, the next task was presented to the participant in a similar manner. The entire study consisted of 336 trials for each participant.

We wanted to conduct the study under outdoor illuminance conditions, because while indoor illuminance varies by ~ 3 orders of magnitude, outdoor illuminance varies by ~ 8 orders of magnitude [19]. However, we could not conduct the study in direct sunlight, because graphics on the Glasstron AR display become almost completely invisible. We also needed to protect the display and other equipment from outdoor weather conditions. We addressed these issues by conducting our study in a covered breezeway overlooking an open area. Since this location required

TABLE 1
Summary of Variables Studied in the Experiment

Independent Variables

participant	24	*counterbalanced*
outdoor background texture (Fig. 6)	4	brick, building, sidewalk, sky
text color	4	white, red, green, cyan
text drawing style (Fig. 7)	4	none, billboard, drop shadow, outline
text drawing style algorithm	2	maximum HSV complement, maximum brightness contrast
repetition	3	1, 2, 3

Dependent Variables

response time	in *milliseconds*
error	0 (*correct*), 1, 2, 3 (*incorrect*)

participants to face south (that is, toward the sun as it moves across the sky), we positioned the participant at the edge of the breezeway, so that their heads (and thus the display) were shaded from the sun, but their vertical field of view was not limited by the breezeway's roof structure. We ran the experiment between 6 April and 10 May 2006, in Blacksburg, Virginia, during which time the sun's elevation varied between 23 degrees and 68 degrees above the horizon.

We conducted studies at 10 a.m., 1 p.m., and 3 p.m., and only on days that met our predetermined natural illuminance lighting requirements (between 2,000 and 20,000 lux). Using the lightmeter displayed in Fig. 4, we measured the amount of ambient illuminance at the participant's position every trial. Our goals were to quantify the effect of varying ambient illumination on task performance and to ensure that the ambient illuminance fell into our established range. However, our current finding is that between-subjects illumination variation, which represents differences in the weather and time of day, was much larger than the variation between different levels of experimental variables. Therefore, we do not report any effects of illuminance as collected at the user's position in this paper.

3.4 Independent Variables

A summary of our independent variables is presented in Table 1. Details of each independent variable follow.

Outdoor background texture. We chose four outdoor background textures to be representative of commonly found objects in urban settings: brick, building, sidewalk, and sky (Fig. 6). Note that three of these backgrounds (all but building) were used in our previous study [7], [8] but at that time were presented to the participant as large posters showing a high-resolution photograph of each background texture. In this new study, we used actual real-world backgrounds. Stimulus strings were positioned so that they were completely contained within each background (Fig. 5).

We kept the brick and sidewalk backgrounds covered when not in use, so that their condition remained constant throughout the study. The sky background varied depending upon cloud cover, haze, etc. and, in some (rare) cases,

Fig. 6. We used four real-world outdoor background textures for the study. Shown above are (clockwise starting in upper left): brick, building, sky, and sidewalk. Stimulus text strings (both upper and lower blocks) were completely contained within the background of interest (as shown in Fig. 5). The images represent the participants' field of view when looking through the display.

would vary widely as cumulus clouds wandered by. We considered including a grass background but were concerned that the color and condition of the grass would vary during the months of April and May, moving from a dormant green-brown color to a bright green color.

Text color. We used four text colors commonly used in computer-based systems: white, red, green, and cyan. We chose white because it is often used in an AR to create labels and because it is the brightest color presentable in an optical see-through display. Our choice of red and green was based on the physiological fact that cones in the human eye are most sensitive to certain shades of red and green [20], [21]. These two text colors were also used in our first study. We

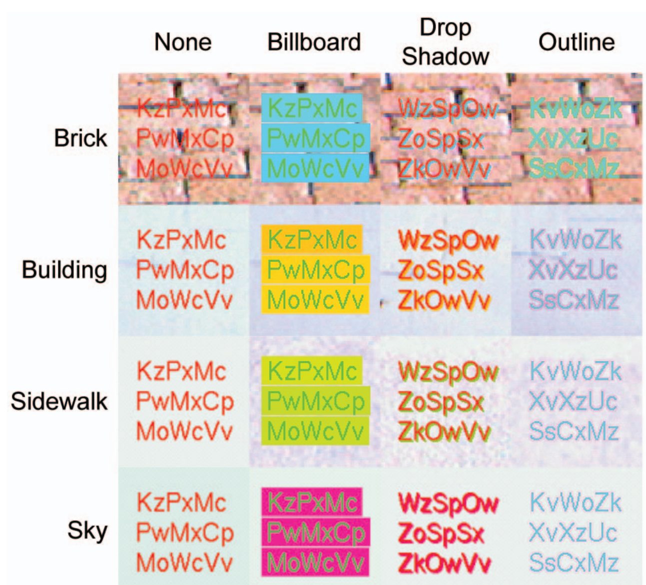

Fig. 7. We used four text drawing styles: none, billboard, drop shadow, and outline (shown on the four outdoor background textures). Note that the thumbnails shown above were subsampled from the participant's complete field of view.

chose cyan to represent the color blue. We chose not to use a "true" blue (0, 0, 255 in RGB color space), because it is a dark color and is not easily visible in optical see-through displays.

Text drawing style. We chose four text drawing styles (Fig. 7): none, billboard, drop shadow, and outline. These are based on previous research in typography, color theory, and HCI text design. We used a sans serif font (Helvetica) and presented the text at a size that appeared approximately two inches tall at a distance of two meters. Text size did not vary during the experiment. None means that text is drawn "as is," without any surrounding drawing style. We included the billboard style because it is commonly used in AR applications and, in other fields, where text annotations are overlaid onto photographs or video images; arguably, it is one of the standard drawing styles used for AR labels. We used *billboard* in our previous study as well [7]. We included *drop shadow* because it is commonly used in print and television media to offset text from backgrounds. We included *outline* as a variant on drop shadow that is visually more salient yet imposes only a slightly larger visual footprint. The outline style is similar to the "anti-interference" font described by Harrison and Vicente [22]. Another motivation for choosing these drawing styles was to compare text drawing styles with small visual footprints (drop shadow, outline) to one with a large visual footprint (billboard).

Text drawing style algorithm. We used two active algorithms to determine the color of the text drawing style: maximum HSV complement and maximum brightness contrast. These were the best active algorithms from our previous study [7]. As discussed above, the input to these algorithms is the average color of the screen-aligned bounding box of the augmenting text. We designed the *maximum HSV complement algorithm* with the following goals: retain the notion of employing color complements, account for the fact that optical see-through AR displays cannot present the color black, and use the HSV color model [23] so we could easily and independently modify saturation. We designed the *maximum brightness contrast algorithm* to maximize the perceived brightness contrast between text drawing styles and outdoor background textures. This algorithm is based on MacIntyre's maximum luminance contrast technique [24], [25]. Both algorithms are described in detail by Gabbard et al. [7].

Repetition. We presented each combination of levels of independent variables three times.

3.5 Dependent Variables

In addition, as summarized in Table 1, we collected values for two dependent variables: response time and error. For each trial, our custom software recorded the participant's four-alternative forced choice (0, 1, 2, or 3) and the participant's response time. For each trial, we also recorded the ambient illuminance at that moment in time, the average background color sampled by the camera, as well as the color computed by the text drawing style algorithm. This additional information allowed us to calculate (post-hoc) pairwise contrast values between text color, text drawing style color, and background color. In this paper, we report on analyses of error and response time data, as well as the pairwise contrast ratio.

3.6 Experimental Design and Participants

We used a factorial nesting of independent variables for our experimental design, which varied in the order they are listed in Table 1, from slowest (participant) to fastest (repetition). We collected a total of

$$\begin{aligned}&24 \text{ (participant)} \times 4 \text{ (background)} \times 4 \text{ (color)}\\&\times [1 \text{ (drawing style} = \text{none)} + [3 \text{ (remaining drawing styles)}\\&\times 2 \text{ (algorithm)}]] \times 3 \text{ (repetition)} = 8,064\end{aligned}$$

response times and errors. We counterbalanced presentation of independent variables using a combination of Latin Squares and random permutations. Each participant saw all levels of each independent variable, so all variables were within participant.

There were 24 participants in this study, 12 males and 12 females, ranging in age from 18 to 34. All participants volunteered and received no monetary compensation; some received a small amount of course credit for participating in the study. We screened all participants, via self-reporting, for color blindness and visual acuity. Participants did not appear to have any difficulty learning the task or completing the experiment.

3.7 Hypotheses

Prior to conducting the study, we made the following hypotheses:

1. The brick background will result in slower and less accurate task performance because it is the most visually complex.
2. The building background will result in faster and more accurate task performance because the building wall faced north and was therefore shaded at all times.
3. Because the white text is brightest, it will result in the fastest and most accurate task performance.
4. The billboard text drawing style will result in the fastest and most accurate task performance since it has the largest visual footprint, and thus, best separates the text from the outdoor background texture.
5. Since the text drawing styles are designed to create visual contrast between the text and the background, the presence of active text drawing styles will result in faster and more accurate task performance than the *none* condition.

3.8 Results

For error analysis, we created an error metric e that ranged from 0 to 3:

$$e = \begin{cases} |c - p| & \text{if } p \in \{1, 2, 3\}, \\ 3 & \text{if } p = 0, \end{cases} \qquad (1)$$

where $e = 0$ to 2 was computed by taking the absolute value of c, the correct number of target letters, minus p, the participant's response. $e = 0$ indicates a correct response, and $e = 1$ or 2 indicates that the participant miscounted the number of target letters in the stimulus string. $e = 3$ is used for trials where users pressed the "0" key (indicating they found the text illegible). We first analyzed a signed-error term but did not find any interesting or significant finding regarding over- versus undercounting, therefore, we used an absolute error term that considers overcounts and undercounts of the same magnitude as equivalent error values. This error metric was used because it is a more robust measure of error (as compared to simply capturing whether a response was correct or incorrect) as it provides a measure of *how* incorrect a response is, and more to the point, is a better indicator of how difficult the text is to read. Our rationale for using the value three for an unreadable stimulus string is that not being able to read the text at all warranted the largest error score, since it gave the participant no opportunity to perform the task. Our error analysis revealed a 14.9 percent error rate across all participants and all 8,064 trials. This error rate is composed of 5.2 percent for $e = 1$, 0.5 percent for $e = 2$, and 9.2 percent for $e = 3$.

For response time analysis, we removed all repetitions of all trials when participants indicated that the text was illegible $(e = 3)$, since these times were not representative of tasks performed under readable conditions. This resulted in 7,324 response time trials (~ 91 percent of 8,054 trials). Overall, we observed a mean response time of 5,780.6 milliseconds (msec), with a standard deviation of 3,147.0 msec.

We used repeated-measures Analysis of Variance (ANOVA) to analyze the error and response time data. We strove for an experiment-wide alpha level of 0.05 of less to denote a main effect. For this ANOVA, the participant variable was considered a random variable, while all other independent variables were fixed. Because our design was unbalanced (the text drawing style *none* had no drawing style algorithm) and because we removed trials for the response time analysis, we could not run a full factorial ANOVA. Instead, we separately tested all main effects and two-way interactions of the independent variables. When deciding which results to report, in addition to considering the p value, the standard measure of effect significance, we considered d, a simple measure of effect size. $d = max - min$, where max is the largest mean, and min the smallest mean of each result. d is given in units of either error or msec.

We also analyzed the pairwise contrast ratios between text color and background color, text color and drawing style color, and drawing style color and background color. We performed ANOVA and correlation analysis, focusing on the luminance contrast ratio, calculated using the Michelson definition [26]:

$$\frac{(\mathrm{L_{max}} - \mathrm{L_{min}})}{(\mathrm{L_{max}} + \mathrm{L_{min}})}, \tag{2}$$

where $\mathrm{L_{max}}$ and $\mathrm{L_{min}}$ are taken from the Y value in CIE XYZ color space and represent the highest and lowest luminance.

3.8.1 Main Effects

Fig. 8 shows the main effect of background on both error $(F(3, 69) = 23.03, p < .001, d = .353 \text{ error})$ and response time $(F(3, 69) = 2.56, p = .062, d = 471 \text{ msec})$. Participants performed most accurately on the building background and made the most errors on the brick background. A similar trend was found for response time. These findings are consistent with hypothesis 1 and hypothesis 2.

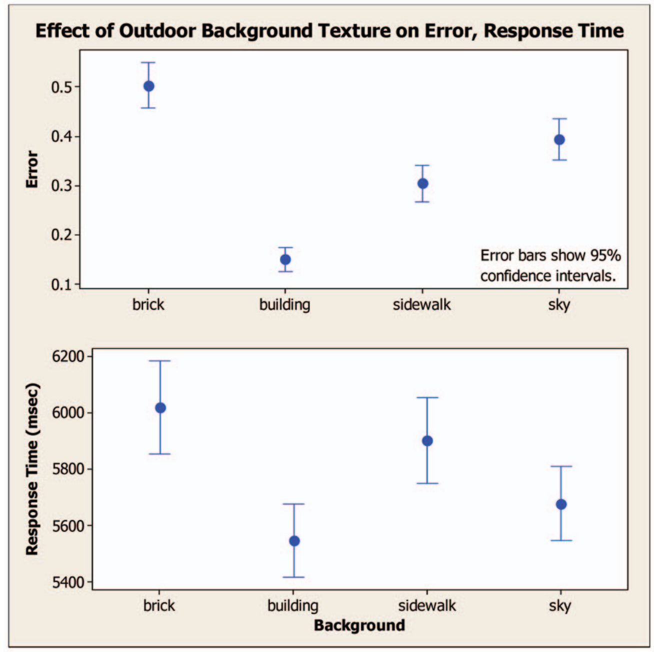

Fig. 8. Effect of background on error $(N = 8,064)$ and response time $(N = 7,324)$. In this and future graphs, N is the number of trials over which the results are calculated.

There was little difference in error under sidewalk and sky conditions $(d = .089 \text{ error})$, and similar results for response time $(d = 225 \text{ msec})$. We observed a relatively large amount of illuminance reflecting off the brick background, and we hypothesize that this illuminance and the complexity of the brick background texture explain why brick resulted in poor performance. Similarly, we hypothesize that the lack of reflected sunlight and the homogeneity of the building background account for the lower errors and faster response times.

Contrary to hypothesis 3, there was no main effect of text color on either error $(F(3, 69) = 2.34, p = .081, d = .075 \text{ error})$ or response time $(\mathrm{F}(3, 69) = 1.81, p = .154, d = 253 \text{ msec})$. However, when we examined the subset of trials, where $\text{drawing style} = none$, we found significant main effects of both error $(F(3, 69) = 5.16, p = .003, d = .313 \text{ error})$ and response time $(F(3, 69) = 8.49, p < .001, d = 1,062 \text{ msec})$. As shown in the right-hand side in Fig. 10 (where algorithm = none), participants performed less accurately and more slowly with red text, while performance with the other text colors (cyan, green, white) was equivalent $(d = .063 \text{ error}$, $d = 166 \text{ msec})$. This result may be due to the luminance limitations of the Glasstron display, resulting in less luminance contrast for red text as compared to cyan, green, and white text. This result is consistent with the finding in our pervious study that participants performed poorly with red text [7], [8] and provides further design guidance that pure red text should be avoided in see-through AR displays used in outdoor settings. Furthermore, together with the lack of an effect of text color over all of the data, these findings suggest that our active drawing styles may enable more consistent participant performance across all text colors, which would

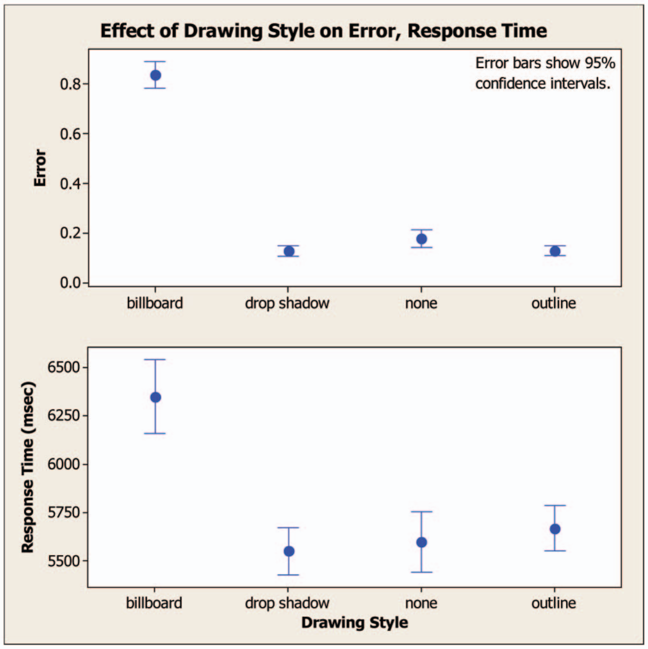

Fig. 9. Effect of text drawing style on error $(N = 8,064)$ and response time $(N = 7,324)$.

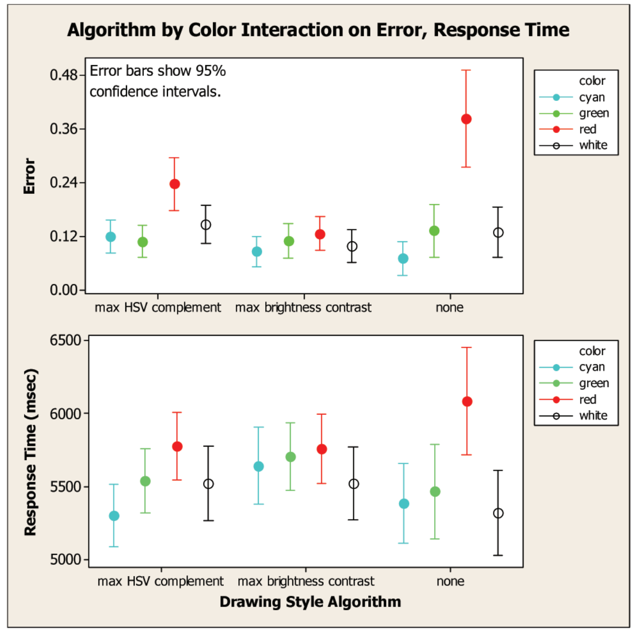

Fig. 10. Effect of drawing style algorithm by text color on error $(N = 5,760)$ and response time $(N = 5,615)$ for the trials where drawing style $\neq$ *billboard*. The right-hand column shows the effect of text color on error $(N = 1,152)$ and response time $(N = 1,109)$ for the trials were drawing style $=$ *none*.

allow AR user interface designers to use text color to encode interface elements.

Fig. 9 shows the main effect of text drawing style on both error $(F(3,69) = 152, p < .001, d = .711 \text{ error})$ and response time $(F(3,69) = 11.6, p < .001, d = 797 \text{ msec})$. In both cases, participants performed less accurately and more slowly with the billboard text drawing style, while performance across the other text drawing styles (drop shadow, outline, none) was equivalent $(d = .051 \text{ error}, d = 118 \text{ msec})$. These findings are contrary to hypothesis 4. As explained in Section 4.3, our active text drawing style algorithms use the average background color as an input to determine a drawing style color that creates a good contrast between the drawing style and the background. Furthermore, the drawing style is a graphical element that surrounds the text, either as a billboard, drop shadow, or outline. A limitation of this approach is that it does not consider the contrast between the text color and the surrounding graphic. Both drop shadow and outline follow the shape of the text letters, while billboard has a large visual footprint (Fig. 7). Therefore, it is likely that in the billboard case, the contrast between text color and the billboard color is more important than the contrast between billboard color and background color (as discussed below), while the opposite is likely true for the drop shadow and outline styles.

Additionally, we propose that there are (at least) two contrast ratios of interest when designing active text drawing styles for outdoor AR: that between the text and the drawing style and that between the text drawing style and the background. Both the size of the text drawing style and whether or not it follows the shape of the letters likely determines which of these two contrast ratios is more important.

Since our billboard style was not compatible with our background-based drawing style algorithms and because it exhibits a large effect size, we removed the billboard drawing style and performed additional analysis on the remaining data set.

Fig. 10 shows that the drawing style algorithm interacted with text color using this subset of data, on both error $(F(6,138) = 2.96, p = .009, d = .313 \text{ error})$ and response time $(\mathrm{F}(6,138) = 2.95, p = .010, d = 1,062 \text{ msec})$. The effect size of text color was the smallest with the maximum brightness contrast algorithm $(d = .040 \text{ error}, d = 221 \text{ msec})$, followed by the maximum HSV complement algorithm $(d = .129 \text{ error}, d = 589 \text{ msec})$ and followed by text drawn with no drawing style and, hence, no algorithm $(d = .313 \text{ error}, d = 1,062 \text{ msec})$. Fig. 11 shows that drawing style algorithm also had a small but significant main effect on error $(F(2,46) = 3.46, p = 0.04, d = .074 \text{ error})$. Participants were most accurate when reading text drawn with the maximum brightness contrast algorithm, followed by the maximum HSV complement algorithm and followed text drawn with no algorithm. Tukey HSD posthoc comparisons [27] verify that *maximum brightness contrast* is significantly different than the other algorithms, while *maximum HSV complement* and *none* do not significantly differ.

It is important to note that the maximum brightness contrast drawing style algorithm does not exist by itself but instead is manifested within the drawing style. More importantly, the algorithm resulted in fewer errors for the sky and brick background conditions (see Fig. 11, bottom), suggesting that there are some backgrounds where the addition of active drawing styles can provide a real benefit (although we did not find an algorithm-by-background interaction for this data set $(F(6,138) = 1.21, p = .304, d = .234 \text{ error})$). Similar to the findings for text color, the effect size of background was the smallest with the maximum brightness contrast algorithm $(d = .089 \text{ error})$, followed by the maximum HSV complement algorithm $(d = .122 \text{ error})$

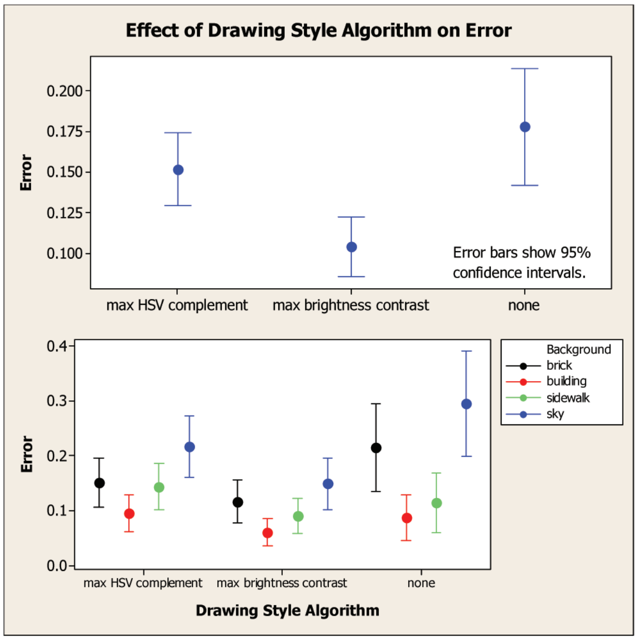

Fig. 11. Effect of text drawing style algorithm on error $(N = 5,760)$ for the trials where drawing style $\neq$ *billboard*.

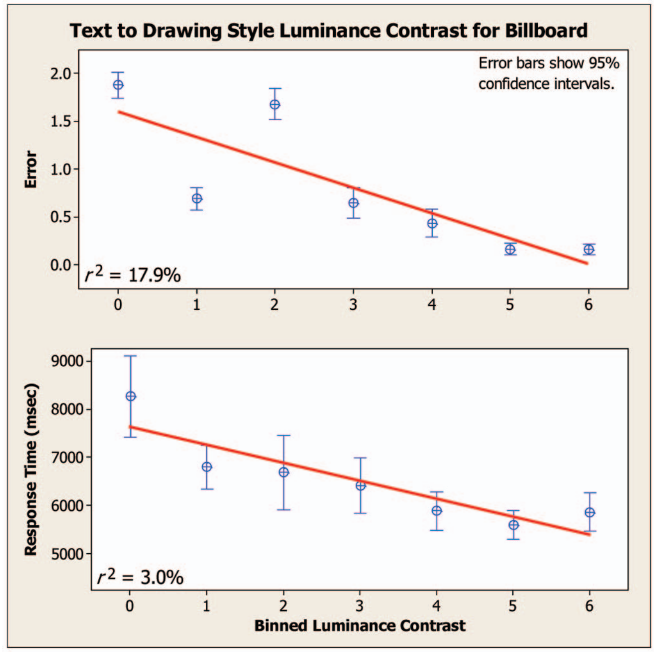

Fig. 12. For the billboard drawing style, correlation between binned luminance contrast ratio (calculated using text color luminance and text drawing style luminance) and error $(\mathrm{N} = 2,304)$ and response time $(\mathrm{N} = 1,709)$.

and followed by text drawn with no drawing style and hence no algorithm $(d = .208\ \mathrm{error})$.

Taken together, these results show that when drawing style $\neq$ *billboard*, the maximum brightness contrast algorithm resulted in the overall best error performance (Fig. 11, top), as well as the least variation in performance over color for error and response time (Fig. 10), and the least variation over background for error (Fig. 11, bottom). More generally, these results suggest that the presence of active text drawing styles can both decrease errors and reduce variability over the absence of any text drawing styles (that is, the *none* condition)—especially those active drawing styles that employ the maximum brightness contrast drawing style algorithm.

3.8.2 Contrast Ratio Analysis

To assist in out contrast ratio analysis, we first calculated all pairwise luminance contrast ratios using (2). We then "binned" the luminance contrast ratios into numbered integer bins ranging from 0 to 10 by multiplying each ratio by 10 and then rounding to the nearest integer. For example, a luminance contrast ratio of 0.32 was assigned to bin 3, a luminance contrast ratio of 0.67 was assigned to bin 7, and so on.

The most compelling results of these analyses were for the billboard drawing style. As hypothesized above, we found that the contrast ratio between the text and the drawing style (that is, billboard) affected user performance more so than, for example, the contrast ratio between text drawing style and background.

For the billboard drawing style, Fig. 12 shows a correlation between binned luminance contrast (calculated using text color luminance and text drawing style luminance) and both error $(\mathrm{r}^2 = 17.9\mathrm{percent}, \mathrm{F}(1, 2, 302) = 504.3, p < .001)$ and response time $(\mathrm{r}^2 = 3.0\mathrm{percent}, \mathrm{F}(1, 1, 707) = 53.0, p < .001)$. As the luminance contrast between the text and drawing style increased, observers both made fewer errors $(\mathrm{d} = 1.596\ \mathrm{error})$ and became faster $(\mathrm{d} = 2,226\ \mathrm{msec})$. Fig. 13 shows the same analysis, this time conducted between the drawing style to background luminance contrast. Here, the correlations were comparatively very weak (error: $\mathrm{r}^2 = 0.0\mathrm{percent}$, $\mathrm{F}(1, 2, 302) = .01,\ \mathrm{p} = .912$; response time: $\mathrm{r}^2 = 0.2\mathrm{percent}$, $\mathrm{F}(1, 1, 707) = 3.75,\ \mathrm{p} = .053)$. As the luminance contrast

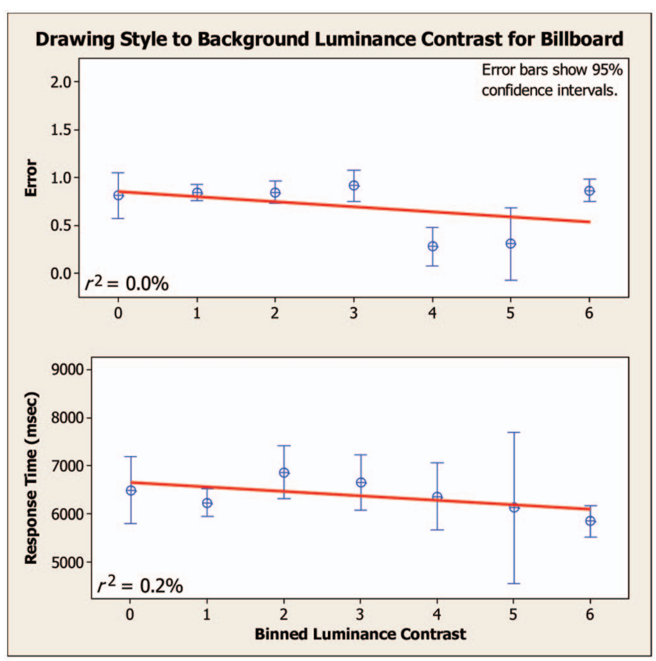

Fig. 13. For the billboard drawing style, correlation between drawing style to background luminance contrast for error $(\mathrm{N} = 2,304)$ and response time $(\mathrm{N} = 1,709)$.

between the drawing style and the background increased, observer errors decreased by $\mathrm{d} = 0.318\ \mathrm{error}$, and response time decreased by $\mathrm{d} = 564\ \mathrm{msec}$. Similar findings were found when we examined the contrast ratio between text and background for the billboard condition. Thus, for drawing styles with larger visual footprints (for example, billboard), we can conclude that the luminance contrast ratio between the text and the billboard is a better predictor of user performance than the luminance contrast ratios between text and background and drawing style and background.

3.9 Implications for Design

Our empirical findings suggest that the presence of active drawing styles effects user performance for text legibility and that as we continue to research and design active drawing styles, we should take into account at least two kinds of contrast ratios: the contrast ratio between the text and the drawing style, as well as the contrast ration between the drawing style and the background. Although not explicitly explored here, there are likely times where a third contrast ratio (text color to background) is of interest—and indeed, in active systems may indicate whether or not an intervening drawing style is even needed at all.

Our findings also suggest that when using a billboard drawing style, maximizing the luminance contrast ratio between the desired text color and the billboard color supports better user performance on text reading tasks.

A finding consistent with our previous study [8] is a clear empirical evidence that user performance on a visual search task, which we believe is the representative of a wide variety of imagined and realized AR applications, is significantly affected by background texture (Fig. 8), text drawing style (Fig. 9), text color (Fig. 10), and active drawing style algorithm (Figs. 10 and 11). These findings suggest that more research is needed to understand how text and background colors interact and how to best design active systems to mitigate performance differences.

4 Lessons Learned from Performing User-Based Studies to Inform Design

As part of the design process and in preparation for user-based studies, it is advantageous to develop sets of design concepts using PowerPoint or other static mockups presented through an AR display, which can help form and refine an understanding of the design space. Moreover, these mockups can help designers identify design parameters that are good candidates for user-based studies. In some cases, it is possible to empirically cull candidate designs and identify candidates that are likely to result in better user performance (as compared to the designs that are culled). This was the approach we used when examining occlusion in the BARS [28].

User-based studies should employ user tasks that are representative but not so specific such that findings cannot be applied throughout the target application or domain. For example, our user task described in this paper required users to visually scan text, discriminate letters, identify patterns, and count target letters. While this task is not an actual task that would be performed in the BARS application, it is representative of visual scanning tasks that employ text as the main user interface element.

User-based studies should be conducted using the equipment that is most likely to be used in the application setting. By doing so, the results of studies are more likely to be applicable to the final application and its supporting hardware. This is especially true for optical see through displays in outdoor settings, where the brightness, color gamut, and optical settings can vary widely. It is also true for any novel input devices that have form factors and or button arrangements. Our studies were run using a Glasstron display, which was not optimal for outdoor use. Specifically, the graphics displayed through the Glasstron are not sufficiently bright for all outdoor conditions. Moreover, we had to construct and affix "horse blinds" to the sides of the display to keep glare from entering participants' eyes through the sides of the display. In the Glasstron's defense, it was not designed for outdoor use but was the only display we had available at that time.

User-based studies should be conducted in the environment that is most likely to be used in the application setting. This is especially true for outdoor settings where lighting can vary depending upon location, time of day, etc. For our observations, lighting issues, setting, context, and so on, all potentially affect user performance. As a result, researchers should strive to match the experimental setting to the application setting as much as possible.

Another lesson we learned: do not employ tracking unless you need to. In cases where the scientific inquiry does not center around or hinge upon tracking (for example, mobile settings, dynamic viewing of objects from various angles, etc.), we have found that eliminating tracker integration expedites the entire process and generally makes setting up and conducing user-based experiment much easier. Instead of tracking, we have either 1) fixed the users head position comfortably using some type of apparatus [5] or 2) presented precaptured static images of the scene in order to physically align the user's view to a controlled view. The latter approach was used in the study presented herein.

When designing user-based studies to inform design, we recommend striving to keep the experimental designs small. Smaller experimental designs help force designers to focus on the most important user interface design factors. Indeed, the design space of the study presented herein initially had 11 independent variables that resulted in just over 6,000 trials, with a mean response time of 5-6 seconds, which would have taken a subject at least eight hours for a fully within-subjects design. Here is another situation where the use of static mockups can help narrow the design space to a tractable set of factors and levels. Since smaller experiments equate to less time per subject (a maximum of two hours from time of arrival to exit is our rule of thumb), they afford running more subjects, which generally enhances the experiment's validity and power.

Moreover, smaller experimental designs are quicker to design, develop, and run, and are also faster and easier to analyze. Along these lines, when performing analysis, focus on the main effects, as well as two-way interactions. Look for the most obvious findings and then move on. The successful application of user-based studies within larger a UE approach relies on the ability to iterate and evolve quickly.

Last, we have learned that by iteratively evolving a design space through user-based studies and evaluation, it is possible to gain insight on novel approaches to solving user interface design problems identified as part of the design/evaluation process. For example, the case study presented herein was the second of two studies performed to examine text legibility in outdoor AR. As described above, the second study employed an active AR testbed to alter the text in real time based on the real-world background texture. The need for an active systems resulted from our analysis of our first user-based study. A related example is the identification of the need for an optical see-through display that can display black (today's optical see through displays use black as transparent).[2] Mobile outdoor AR would benefit greatly from a display that could present a larger color gamut, specifically in the darker regions. Indeed, both of these examples show that iteratively evolving the design space through user-based studies at least introduces the potential for innovation.

5 Applicability to Other Emerging Technologies

Along with AR, there are other emerging technologies that would likely benefit from a UE approach that utilizes user-based studies to optimize user interface designs. For example, as the use of cell phones and handhelds increase, we see designs moving away from the standard WIMP metaphor toward more novel interaction techniques such as the iPhone's use of accelerometers and touch sensing.

Handhelds are also starting to serve as the platform for mobile handheld AR. Here again, interacting with information overlaid onto the real world with a small form factor will introduce some interesting design challenges—solved either through inspiration or empirical observations of users working with suites of candidate designs.

As ubiquitous computing matures, the notion of having access to computing power at all times but without the bother of cumbersome cords or fixed location will require the development of novel display (in the broadest sense of the word) and interaction techniques. While some user interface and interaction techniques can be leveraged from related technologies, it is likely the case that guidelines for design much less standards for design will emerge overnight.

6 Conclusion

We have presented a modified UE approach to design that employs a combination of user interface design, user-based studies and expert evaluation to iteratively design a usable user interface, as well as refine designers' understanding of a specific design space. We have presented a case study involving text legibility in outdoor AR to illustrate how user-based studies can inform design. Finally, we have presented lessons learned in terms of the product (that is, specific design recommendations and guidelines), as well as the process (that is, recommendations on how to conduct a user-based experiment to inform design).

In the near term, we will be fleshing out more details of the proposed UE approach and identify specific modifications needed to support design, development, and evaluation of emerging technologies. Specifically, we will be examining some of the challenges of performing domain analyses, as well as formative usability evaluation using these technologies.

We have recently conducted a follow-on study that systematically varied the contrast ratio between text color and text drawing style color. The goal of this study was to gain more insight on minimum contrast needed between text and a billboard background for effective task performance on text legibility tasks. We intend to analyze the results of this study and optimally identify contrast thresholds or ranges in which user performance is unhindered. Assuming we identify these thresholds, we will use this knowledge to inform more sophisticated drawing style algorithms and to determine appropriate text drawing styles under varying environmental conditions.

With respect to further understanding the design space of text legibility in outdoor AR, we intend to design and conduct further studies on this topic. Specifically, we intend to design a study that systematically varies and controls the pairwise contrast ratios between text color, text drawing style color, and outdoor background textures. By designing a study that explicitly controls these factors, we hope to be able to better understand the relative importance of each pairwise contrast ratio for our given text drawing styles (including the none drawing style).

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Egocentric Depth Judgments in Optical, See-Through Augmented Reality

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Abstract—A fundamental problem in optical, see-through augmented reality (AR) is characterizing how it affects the perception of spatial layout and depth. This problem is important because AR system developers need to both place graphics in arbitrary spatial relationships with real-world objects, and to know that users will perceive them in the same relationships. Furthermore, AR makes possible enhanced perceptual techniques that have no real-world equivalent, such as *x-ray vision*, where AR users are supposed to perceive graphics as being located behind opaque surfaces. This paper reviews and discusses protocols for measuring egocentric depth judgments in both virtual and augmented environments, and discusses the well-known problem of depth underestimation in virtual environments. It then describes two experiments that measured egocentric depth judgments in AR. Experiment I used a perceptual matching protocol to measure AR depth judgments at medium and far-field distances of 5 to 45 meters. The experiment studied the effects of upper versus lower visual field location, the x-ray vision condition, and practice on the task. The experimental findings include evidence for a switch in bias, from underestimating to overestimating the distance of AR-presented graphics, at $\sim$ 23 meters, as well as a quantification of how much more difficult the x-ray vision condition makes the task. Experiment II used blind walking and verbal report protocols to measure AR depth judgments at distances of 3 to 7 meters. The experiment examined real-world objects, real-world objects seen through the AR display, virtual objects, and combined real and virtual objects. The results give evidence that the egocentric depth of AR objects is underestimated at these distances, but to a lesser degree than has previously been found for most virtual reality environments. The results are consistent with previous studies that have implicated a restricted field-of-view, combined with an inability for observers to scan the ground plane in a near-to-far direction, as explanations for the observed depth underestimation.

Index Terms—Artificial, augmented, and virtual realities, ergonomics, evaluation/methodology, screen design, experimentation, measurement, performance, depth perception, optical see-through augmented reality.

1 Introduction

Optical, see-through augmented reality (AR) is the variant of AR where graphics are superimposed on a user's view of the real world with optical, as opposed to video, combiners. Because optical, see-through AR (simply referred to as "AR" for the rest of this paper) provides direct, heads-up access to information that is correlated with a user's view of the real world, it has the potential to revolutionize the way many tasks are performed. In addition, AR makes possible enhanced perceptual techniques that have no real-world equivalent. One such technique is *x-ray vision*, where the intent is for AR users to accurately perceive objects which are located behind opaque surfaces.

The AR community is applying AR technology to a number of unique and useful applications [1]. The application that motivated the work described here is mobile, outdoor AR for situational awareness in urban settings (the Battlefield Augmented Reality System (BARS) [19]). This is a very difficult application domain for AR; the biggest challenges are outdoor tracking and registration, outdoor display hardware, and developing appropriate AR display and interaction techniques.

In this paper, we focus on AR display techniques, in particular, how to correctly display and accurately convey depth. This is a hard problem for several reasons. Current head-mounted displays are compromised in their ability to display depth, because they often dictate a fixed accommodative focal depth, and they restrict the field of view. Furthermore, it is well known that distances are consistently underestimated in VR scenes depicted in head-mounted displays [5], [16], [21], [23], [34], [36], but the reasons for this phenomenon are not yet clear. In addition, unlike virtual reality, with AR users see the real world, and therefore graphics need to appear to be at the same depth as colocated real-world objects, even though the graphics are physically drawn directly in front of the eyes. Furthermore, there is no real-world equivalent to x-ray vision, and it is not yet understood how the human visual system reacts to information displayed with purposely conflicting depth cues, where the depth conflict itself communicates useful information.

2 Background and Related Work

2.1 Depth Cues and Cue Theory

Human depth perception delivers a vivid three-dimensional perceptual world from flat, two-dimensional, ambiguous retinal images of the scene. Current thinking on how the human visual system is able to achieve this performance emphasizes the use of multiple *depth cues*, available in the

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scene, that are able to resolve and disambiguate depth relationships into reliable, stable percepts. *Cue theory* describes how and in which circumstances multiple depth cues interact and combine. Generally, 10 depth cues are recognized (Howard and Rogers [11]):

1. binocular disparity,
2. binocular convergence,
3. accommodative focus,
4. atmospheric haze,
5. motion parallax,
6. linear perspective and foreshortening,
7. occlusion,
8. height in the visual field,
9. shading, and
10. texture gradient.

Real-world scenes combine some or all of these cues, with the structure and lighting of the scene determining the relative salience of each cue. Although *depth cue interaction* models exist (Landy et al. [18]), these were largely developed to account for how stable percepts could arise from a variety of cues with differing salience. The central challenge in understanding human depth perception in AR is determining how stable percepts can arise from inconsistent, sparse, or purposely conflicting depth cues, which arise either from imperfect AR displays, or from novel AR perceptual situations such as x-ray vision. Therefore, models of AR depth perception will likely inform both applied AR technology as well as basic depth cue interaction models.

2.2 Near, Medium, and Far-Field Distances

Depth cues vary both in their salience across real-world scenes, and in their effectiveness by distance. Cutting [6] has provided a useful taxonomy and formulation of depth cue effectiveness by distances that relate to human action. He divided perceptual space into three distinct regions, which we term near-field, medium-field, and far-field. The *near field* extends to about 1.5 meters: It extends slightly beyond arm's reach, it is the distance within which the hands can easily manipulate objects, and within this distance, depth perception operates almost veridically. The *medium field* extends from about 1.5 meters to about 30 meters: It is the distance within which conversations can be held and objects thrown with reasonable accuracy; within this distance, depth perception for stationary observers becomes somewhat *compressed* (items appear closer than they really are). The *far field* extends from about 30 meters to infinity, and as distance increases, depth perception becomes increasingly compressed. Within each of these regions, depth cues vary in their availability, salience, and potency.

2.3 Egocentric Distance Judgment Techniques

Researchers have long been interested in measuring the perception of distance, but, faced with the classic problem that perception is an invisible cognitive state, have had to find measurable quantities that can be related to the perception of distance. Therefore, they have devised experiments where distance perception can be inferred from distance *judgments*. The most general categorization of distance judgments is egocentric or exocentric: *egocentric* distances are measured from an observer's own view point, while *exocentric* distances are measured between different objects in a scene. Loomis and Knapp [21] and Foley [10] review and discuss the methods that have been developed to measure judged egocentric distances.

There have been three primary methods: *verbal report*, *perceptual matching*, and *open-loop action-based tasks*. With *verbal report* [10], [16], [21], [23], observers verbally estimate the distance to an object, typically using whatever units they are most familiar with (e.g., feet, meters, or multiples of some given referent distance). Observers have also verbally estimated the size of familiar objects [21], which are then used to compute perceived distance. *Perceptual matching* tasks [9], [10], [22], [30], [37] involve the observer adjusting the position of a target object until it perceptually matches the distance to a referent object. Perceptual matching is an example of an *action-based task*; these tasks involve a physical action on the part of the observer that indicates perceived distance. Action-based tasks can be further categorized into open-loop and closed-loop tasks. In an *open-loop* task, observers do not receive any visual feedback as they perform the action, while in a *closed-loop* task they do receive feedback. By definition, perceptual matching tasks are closed-loop action-based tasks.

A wide variety of *open-loop action-based tasks* have been employed. For all of these tasks, observers perceive the egocentric distance to an object, and then perform the task without visual feedback. The most common open-loop action-based task has been *blind walking* [5], [16], [21], [23], [36], [37], where observers perceive an object at a certain distance, and then cover their eyes and walk until they believe they are at the object's location. Blind walking has been found to be very accurate for distances up to 20 meters, and there is compelling evidence that blind walking accurately measures the percept of egocentric distance (Loomis and Knapp [21]). Because of these benefits, blind walking has been widely used to study egocentric depth perception at medium and far-field distances, in both real-world and VR settings. A closely related technique is *imagined blind walking* [7], [26], where observers close their eyes and imagine walking to an object while starting and stopping a stopwatch; the distance is then computed by multiplying the time by the observers' normal walking speed. Yet another variant is *triangulation by walking* [21], [34], [36], where observers view an object, cover their eyes, walk a certain distance in a direction oblique to the original line of sight, and then indicate the direction of the remembered object location; their perception of the object's distance can then be recovered by simple trigonometric calculations. Near-field distances have been studied by *open-loop pointing* tasks [10], [25], where observers indicate distance with a finger or manipulated slider that is hidden from view.

In addition, some researchers have used *forced-choice* tasks [20], [29], [30] to study egocentric depth perception. In forced-choice tasks, observers make one of a small number of discrete depth judgment choices, such as whether one object is closer or farther than another; or at the same or a different depth; or at a near, medium, or far depth, etc. These tasks tend to use a large number of repetitions for a small number of observers, and can employ psychophysical techniques to measure and analyze the judged depth [29], [30].

Finally, although depth judgment tasks are considered the best method available for measuring the egocentric percept of distance and have been widely used, researchers have determined that they can be influenced by cognitive factors that are unrelated to actual egocentric distance. For example, Decety et al. [7] and Proffitt [27] have argued that distance judgments are influenced by the amount of energy observers anticipate expending to traverse the distance. Proffitt [27] and collaborators have further observed that distance judgments are influenced by the possibility of injury, by the observer's current emotional state, and even by social factors such as whether or not the observer owns the item to which distances are judged.

2.4 The Virtual Reality Depth Underestimation Problem

Over the past several years, many studies have examined egocentric depth perception in VR environments. A consistent finding has been that *egocentric depth is underestimated* when objects are viewed on the ground plane, at near to medium-field distances, and the VR environment is presented in a head-mounted display (HMD) [5], [16], [21], [23], [28], [34], [36]. As discussed above, most of these studies have utilized open-loop action-based tasks, although the effect has been observed with perceptual matching tasks as well [37]. These studies have examined various theories as to why egocentric depth is underestimated, and have found evidence that underestimation is caused by an HMD's limited field-of-view [37]; that underestimation is *not* caused by an HMD's limited field-of-view [5], [16]; that the weight of the HMD itself might contribute to the phenomenon [36]; that monocular versus stereo viewing does not cause it [5]; that the quality of the rendered graphics does not cause it [34]; that the effect persists even when observers see live video of the real world in an HMD [23]; that the effect might exist when VR is displayed on a large-format display screen as well [26]; that the effect might disappear when observers know that the VR room is an accurate model of the physical room in which they are located [13]; that the amount of underestimation is significantly reduced by as little as 5 to 7 minutes of practice with feedback [24], [28]; and that the underestimation effect can be compensated by modifying the way the graphics are rendered [17]. In summary, the egocentric distance underestimation effect is real, and although its parameters are being explored, it is not yet fully understood.

2.5 Previous AR Depth Judgment Studies

There have been a small number of studies that have examined depth judgments with optical, see-through AR displays. Ellis and Menges [9] summarize a series of AR depth judgment experiments, which used a perceptual matching task to examine near-field distances of 0.4 to 1.0 meters, and studied the effects of an occluding surface (the x-ray vision condition), convergence, accommodation, observer age, and monocular, biocular, and stereo AR displays. They found that monocular viewing degraded the depth judgment, and that the x-ray vision condition caused a change in vergence angle which resulted in depth judgments being biased toward the observer. They also found that cutting a hole in the occluding surface, which made the depth of the virtual object physically plausible, reduced the depth judgment bias. McCandless et al. [22] used the same experimental setup and task to additionally study motion parallax and AR system latency in monocular viewing conditions; they found that depth judgment errors increased systematically with increasing distance and latency. Rolland et al. [29], in addition to a substantial treatment of AR calibration issues, discuss a pilot study at near-field distances of 0.8 to 1.2 meters, which examined depth judgments of real and virtual objects using a forced-choice task. They found that the depth of virtual objects was overestimated at the tested distances. Rolland et al. [30] then ran additional experiments with an improved AR display, which further examined the 0.8 meter distance, and compared forced-choice and perceptual matching tasks. They found improved depth accuracy and no consistent depth judgment biases. Jerome and Witmer [14] used a perceptual matching task as well as verbal report to examine distances from 1.5 to 25 meters. They found that the depth of real-world objects were judged more accurately than virtual objects, but their dependent measure does not allow the error to be categorized as underestimation or overestimation. They also found a very interesting interaction between error and gender. Kirkely [15] used verbal report to study the effect of the x-ray vision condition, the ground plane, and object type (real objects, realistic virtual objects (e.g., a chair), and abstract virtual objects (e.g., a sphere)), on monocularly-viewed objects at distances from 3 to 33.5 meters. He found that the x-ray vision condition reduced performance, placing objects on the ground plane improved performance, and that real objects resulted in the best performance, realistic virtual objects resulted in intermediate performance, and abstract virtual objects resulted in the worst performance. Livingston et al. [20] used a forced-choice task to examine graphical parameters such as drawing style, intensity, and opacity on occluded AR objects at far-field distances of 60 to 500 meters. They found that certain parameter settings were more effective for their task.

Taken together, these studies have just begun to explore how depth perception operates in AR displays. In particular, only two previous studies have examined AR depth perception in the medium-field to far-field, which is an important range of distances for many imagined outdoor AR applications. In this paper, we describe two AR egocentric depth judgment experiments that have studied this range of distances. Experiment I used a perceptual matching task, and Experiment II used verbal report and blind walking tasks. Furthermore, Experiment II is the first reported AR depth study to use the open-loop action-based task of blind walking, and as discussed above, in VR open-loop action-based tasks have been the most wildly used task category.

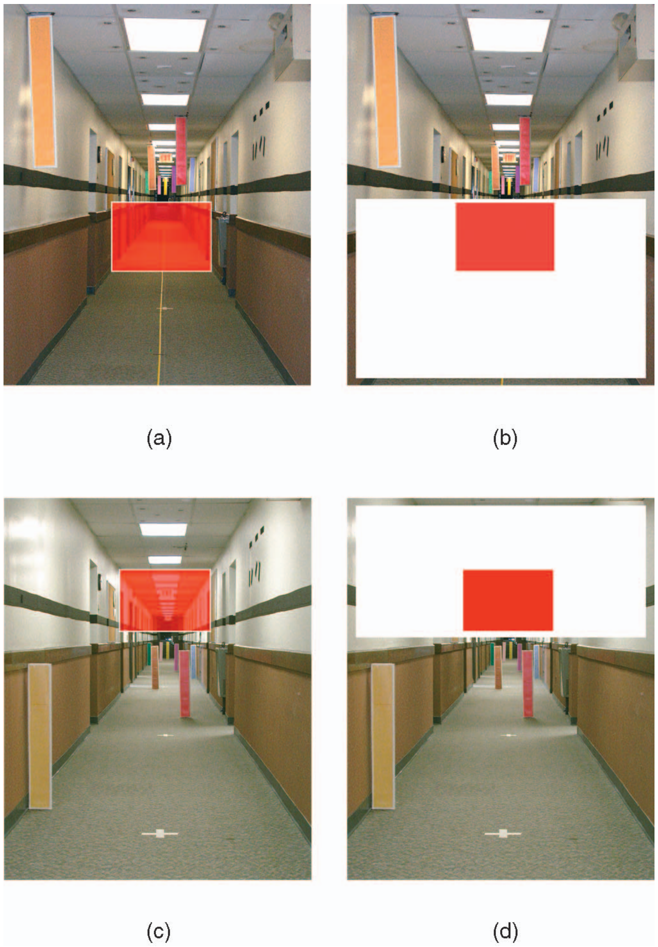


Fig. 1. The experimental setting and layout of the real-world referents and the virtual target rectangle. Observers manipulated the depth of the target rectangle to match the depth of the real-world referent with the same color (red in this example). Note that these images are not photographs taken through the actual AR display, but instead are accurate illustrations of what observers saw. (a) Referents on *ceiling*, ocluder *absent*. (b) Referents on *ceiling*, occluder *present*. (c) Referents on *floor*, occluder *absent*. (d) Referents on *floor*, occluder *present*.

3 Experiment I: Perceptual Matching Protocol

3.1 Experimental Task and Setting

In Experiment I,[1] we used a perceptual matching task to study depth judgments of medium-field to far-field distances of 5.25 to 44.31 meters. Fig. 1 shows the experimental setting. Observers sat on a stool at one end of a long hallway, and looked through an optical, see-through AR display mounted on a frame. Observers saw a series of eight real-world *referents*, approximately positioned evenly down the hallway (Fig. 1). Each referent was a different color. The AR display showed a virtual *target*, which we drew as a semitransparent rectangle that horizontally filled the hallway, and vertically extended about half of the hallway's height. Our target and task was motivated by our initial problem domain, outdoor augmented reality in urban settings [19], which required users to visualize the spatial layout of rectangular building components, such as walls, floors, doors, etc., within a radius of one to several blocks. The visualized rectangular building components typically abutted other parts of the building, such as the hallway in our experimental setting.

TABLE 1
Independent Variables and Levels, and Dependent Variables, for Experiment I

Independent Variables				
observer	8	(random variable)		
height in visual field	2	ceiling, floor		
occluder	2	present, absent		
distance	8	**Distance (Meters)**	**Angular Size (° Visual Angle)**	**Color**
		5.25	1.75	orange
		11.34	.808	red
		17.42	.526	brown
		22.26	.412	blue
		27.69	.331	purple
		33.34	.275	green
		38.93	.235	pink
		44.31	.206	yellow
repetition	10	1, 2, 3, 4, 5, 6, 7, 8, 9, 10		
Dependent Variables				
judged distance	measured by perceptual matching, *meters*			
absolute error	| *judged distance – distance* |, *meters*			
error	*judged distance – distance, meters*			

Observers adjusted the target's depth position in the hallway with a trackball. For each trial, our software drew the target rectangle at a random initial depth position; it drew the target rectangle with a white border, and colored the target interior to match the color of one of the referents (Fig. 1). The observer's task was to adjust the target's depth position until it matched the depth of the referent with the same color. When the observer believed the target depth matched the referent depth, they pressed a mouse button on the side of the trackball. This made the target disappear; the display then remained blank for approximately one second, and then the next trial began. For the display device we used a Sony Glasstron LDI-D100B stereo optical see-through display. It displays 800×600 (horizontal by vertical) pixels in a transparent window which subtends $27° \times 20°$[2] and, thus, each pixel subtends approximately $.033° \times .033°$.

3.2 Variables and Design

3.2.1 Independent Variables

The independent variables are summarized in Table 1. We recruited eight *observers* from a local population of scientists and engineers. As shown in Fig. 1, we placed the referents at two different *heights in the visual field*: we mounted the referents either on the *ceiling* or the *floor*. Our experimental control program rendered the target in the opposite field of view as the referents. As discussed above, we were interested in understanding AR depth perception in the x-ray vision condition, so we varied the presence of an occluding surface. When the *occluder* was *absent* (Figs. 1a and 1c), observers could see the hallway behind the target. When the *occluder* was *present* (Figs. 1b and 1d), we mounted a heavy rectangle of

1. This experiment has been previously described by Swan et al. [32]; this section summarizes the experiment and its most interesting results.

2. Angular measures in this paper are in degrees of visual arc.

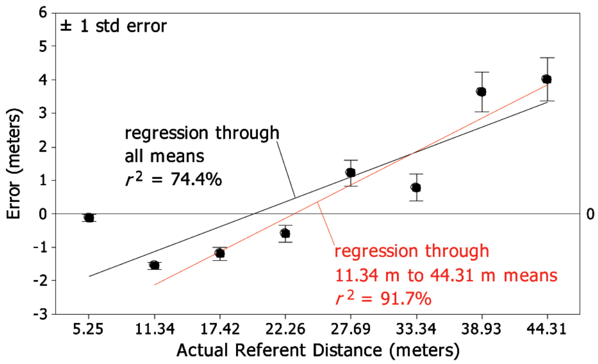


Fig. 2. The effect of distance on error $(N = 2,560)$, which exhibits a strong linear regression beginning at 11.34 meters. This reveals a switch in bias from underestimating to overestimating target distance at ~ 23 meters.

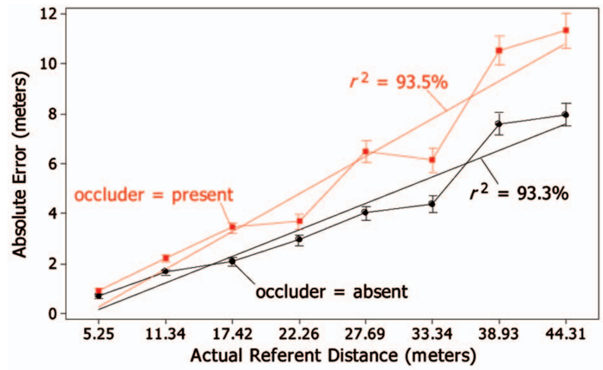


Fig. 3. Effect of occluder by distance on absolute error $(N = 2,560)$. Observers had more error in the occluded (x-ray vision) condition (red line and points) than in the nonoccluded condition (black and points), and the difference between the occluded and nonoccluded conditions increased with increasing distance.

foamcore posterboard across the observer's field-of-view, which occluded the view of the hallway behind the target. We placed the eight referents at the *distances* from the observer indicated in Table 1. We built the referents out of triangular shipping boxes, which measured 15.3 cm wide by 96.7 cm tall. We covered the boxes with the colors listed in Table 1. We created the colors by printing single-colored sheets of paper with a color printer. To increase the contrast of the referents against the hallway background, we created a border around each color with white gaffer's tape. We affixed the referents to the ceiling and floor with velcro. We presented each *repetition* of the other independent variables 10 times.

3.2.2 Dependent Variables

For each trial, observers manipulated a trackball to place the target at their desired depth down the hallway, and pressed the trackball's button when they were satisfied. The trackball produced 2D cursor coordinates, and we converted the y-coordinate into a depth value with the perspective transform of our graphics pipeline; we used this depth value to render the target rectangle. When an observer pressed the mouse button, we recorded this depth value as the observer's *judged distance*. As indicated in Table 1, we used the judged distance to calculate two dependent variables, *absolute error* and *error*. An *absolute error* or *error* close to 0 indicates an accurately judged distance. An $error > 0$ indicates an overestimated judged distance, while an $error < 0$ indicates an underestimated judged distance.

3.2.3 Experimental Design and Procedure

We used a factorial nesting of independent variables for our experimental design, which varied in the order they are listed in Table 1, from slowest (observer) to fastest (repetition). We collected a total of 2,560 data points (eight observers × two fields of view × two occluder states × eight distances × 10 repetitions). We counterbalanced presentation order with a combination of Latin squares and random permutations. Each observer saw all levels of each independent variable, so all variables were within-subject.

3.3 Results and Discussion

Here, we discuss the main results qualitatively; full statistical details are given in Swan et al. [32]. Fig. 2[3] shows that error increased linearly with increasing distance ($r^2 = 74.4\%$; black line in Fig. 2). However, the 5.25 meter referent weakens the linear relationship; it is likely close enough that near-field distance cues are still operating. The linear relationship between error and distance increases when analyzed for referents 2-8 ($r^2 = 91.7\%$; red line in Fig. 2). Even more interesting is a shift in bias from underestimating (referents 2-4) to overestimating (referents 5-8) distance. The bias shift occurs at around 23 meters, which is where the red line in Fig. 2 crosses zero meters of error. Foley [10] found a similar bias shift, from underestimating to overestimating distance, when studying binocular disparity in isolation from all other depth cues. He found that the shift occurred in a variety of perceptual matching tasks, and although its magnitude changed between observers, it was reliably found. However, in Foley's tasks, the point of veridical performance was typically found at closer distances of 1-4 meters. The similarity of this finding to Foley's suggests that stereo disparity may be an important depth cue in this experimental setting, although the strength of stereo disparity weakens throughout the medium-field range. It seems likely that linear perspective is also an important depth cue here.

Fig. 3 shows an occluder by distance interaction effect on absolute error. When an occluder was present (the x-ray vision condition), observers had more error than when the occluder was absent, and the difference between the occluder present and occluder absent conditions increased with increasing distance. Fig. 3 shows a linear modeling of the occluder present condition (red line), which explains $r^2 = 93.5\%$ of the observed variance, and a linear modeling of the occluder absent condition (black line), which explains $r^2 = 93.3\%$ of the observed variance. These two linear models allow us to estimate the magnitude of the occluder effect according to distance:

$$y_{present} - y_{absent} = .08x - .33,$$

where y_{present} is the occluder present (red) line, y_{absent} is the occluder absent (black) line, and x is distance. This equation says that for every additional meter of distance, observers made 8 cm of additional error in the occluder present versus the occluder absent condition.

3. In this and future graphs, N is the number of data points that the graph summarizes.

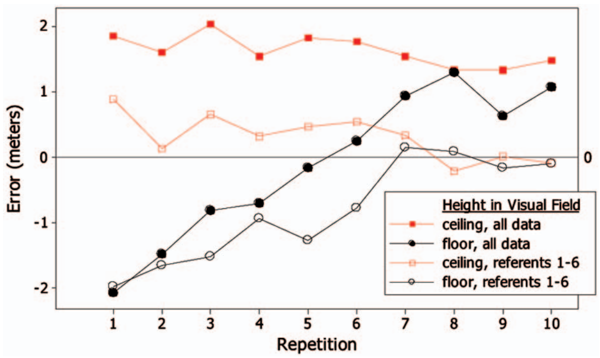


Fig. 4. Effect of height in the visual field by repetition on error ($N = 2,560$). Solid shapes (■, •) are means for all the data; hollow shapes (□, ○) are means for the first six referents. Squares (■, □) are referents mounted on the ceiling; circles (•, ○) are referents mounted on the floor. For clarity, standard error bars are not shown.

Fig. 4 shows an interesting interaction between height in the visual field and repetition. The solid shapes (■, •) show the interaction for all of the data. When the referents were mounted on the ceiling (■), observers overestimated their distance by about 1.5 meters, and when the referents were mounted on the floor (•), observers began with an underestimation (low repetitions), and with practice, by repetition 8 matched the overestimation of the ceiling-mounted referents. The general bias toward overestimation can be explained by the overestimation of the last two referents, as seen in Fig. 2. In Fig. 4, the hollow shapes (□, ○) show the same interaction when the last two referents are removed. When the referents were mounted on the ceiling (□), observers did not show a bias, and by repetition 7 were quite accurate. For referents mounted on the floor (○), observers initially demonstrated the same underestimation as they did for the full data set, and with practice, by repetition 7 matched the veridical performance of the ceiling-mounted referents (□).

This interaction is puzzling. We hypothesize that the underestimation of the first two or three floor-mounted referents (○) is similar to the underestimation that has been demonstrated in VR environments, and that the underestimation's disappearance is a practice effect, which has not been seen in previous experiments because open-loop action-based tasks such as blind walking typically only have 1-3 repetitions. This hypothesis is consistent with the findings of Mohler et al. [24] and Richardson and Waller [28], who found that as little as three additional repetitions of blind walking (but with feedback) significantly reduced the amount of underestimation. On the other hand, the ceiling-mounted referents (□), which are hanging at eye level, do not show underestimation. Among the very few studies to examine the egocentric distance of ceiling-mounted referents is Dilda et al. [8], who used a perceptual matching task that is very similar to the one we used, and found that the distance was overestimated by 10 percent. Interestingly, in Fig. 4, for the first three repetitions the difference between the ceiling (□) and floor (○) referents is also roughly 10 percent.

4 Experiment II: Blind Walking and Verbal Estimation Protocol

Our experiences conducting Experiment I motivated us to design and conduct an experiment which replicated the type of depth judgment task and medium-field setting that has been most often studied in VR. Experiment II utilized the depth judgment protocols of 1) blind walking and 2) verbal report to measure egocentric distance perception of ground-based objects in an AR head-mounted display (HMD). We again studied medium-field distances, this time from 3 to 7 meters. As discussed previously, the VR egocentric depth perception literature describes a number of studies utilizing blind walking [5], [16], [21], [23], [36] and verbal report [10], [16], [21], [23], at distances ranging from ~ 2 to ~ 25 meters. Therefore, Experiment II is more directly comparable to the VR depth perception literature —the main difference being the use of a see-through AR display as opposed to an opaque VR display. Our motivation was to further characterize the depth underestimation phenomena in AR, as well as to study depth judgments of 1) virtual objects and 2) virtual objects that augment the appearance of real objects. As a control condition, we also studied depth judgments of 3) real objects seen with an unencumbered view, and 4) real objects seen through the AR HMD display.

4.1 Experimental Setup and Task

Observers judged the distance to both a physical referent object (Fig. 5a), as well as a virtual model of the referent object. Our referent object was a wooden pyramid, 23.5 cm tall, with a square base of 23.5 cm. Our display device was a Sony Glasstron LDI-100B monoscopic (biocular), optical see-through HMD. Our HMD displays 800×600 (horizontal by vertical) pixels in a transparent window which subtends $27° \times 20°$, and thus each pixel subtends approximately $.033° \times .033°$. This window is approximately centered in a larger semitransparent frame, which is tinted like sunglasses and so attenuates the brightness of the real world. The outer edge of this frame subtends $66° \times 38°$. Because our HMD is monoscopic, we used an anaglyphic stereo technique to give observers a stereo disparity depth cue. We presented the virtual referent in blue to the left eye and red to the right eye (Fig. 5a), and we attached appropriately colored red and blue plastic filters to the inside of the HMD. We ordered the filters from a supplier of 3D anaglyphic stereo equipment; their colors matched the red and blue produced from common monitors. For each eye, there was negligible ghosting through the other eye's filter. The resulting virtual object appeared neither red nor blue, but instead a shade of white. There was also a subtle shimmering effect, which did not disrupt the sense that the virtual referent object was located in a definite position in space. We rendered the back line of the virtual object with a dashed appearance, to graphically suggest that it was behind the front lines.

Attaching the red and blue filters to the HMD further attenuated the brightness of the real world. Although we set the display opacity to its most transparent setting, it was difficult to see the real world, and the physical referent object,

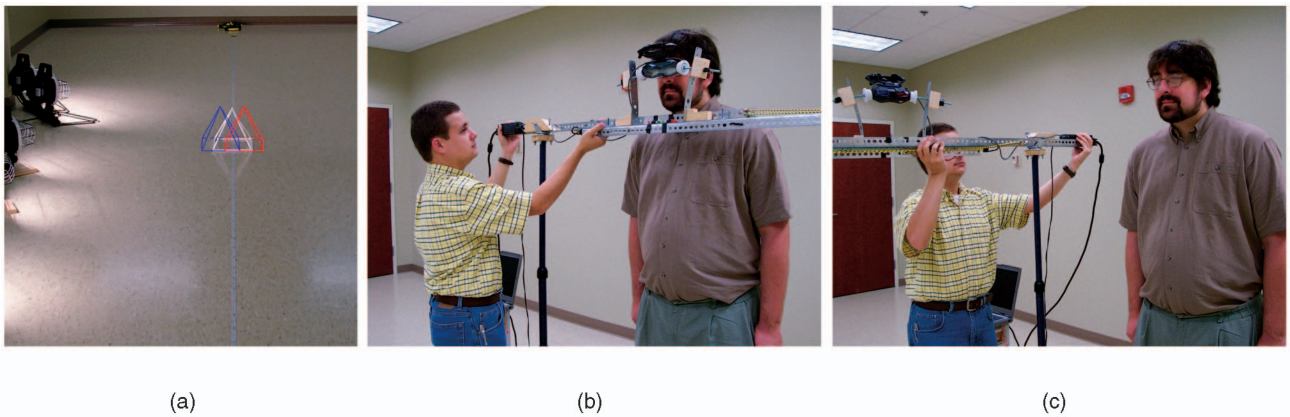


Fig. 5. (a) Observer's view of the real-world referent object, illuminated by the halogen lights, and the virtual referent object (the $real + virtual + HMD$ environment). Observers viewed the virtual object in red/blue anaglyphic stereo. We rendered the backmost line of the virtual object with a dashed appearance, which further enhanced the sense that the virtual and real objects were merged. Note that we created this image using video see-through AR, while observers used optical see-through AR. (b) Observer looking through the frame-mounted AR HMD during a blind walking trial. An experimenter is prepared to swing the frame out of the way. (c) The experimenter has swung the frame out of the way, and the observer is now free to walk forward.

under normal indoor illumination conditions. Therefore, like other studies that have utilized Glasstron displays [14], we illuminated the referent object with six 600-watt halogen lamps (Fig. 5a), which provided enough illumination so that the object could be readily perceived through the display. In addition, we painted the physical referent object white, both to match the virtual pyramid, and to better reflect the illumination of the halogen lamps. We adjusted the HMD's brightness setting so that the virtual object matched the brightness of the real object. We corrected the display for an optical barrel distortion effect using the 2D polygonal grid-based texture mapping technique initially described by Watson and Hodges [35] and refined by Bax [2]; we separately calibrated a 16×12 cell grid for the left and right display channels. Our display had a nonadjustable interpupilary separation, so we measured observers' interpupilary distance and eye height, and modeled these parameters in software. Our display also had a nonadjustable accommodative demand of 1.2 meters.

As mentioned above, we wanted to study the condition where the virtual referent augmented the appearance of the physical referent. This meant that we needed to achieve a very precise alignment between the virtual and physical referents—more precise than is possible with current 6 degree-of-freedom tracking technology. Therefore, similar to Experiment I, we mounted the AR HMD on a rigid frame, supported by two tripods. We adjusted the height of the tripods so that each observer could comfortably look through the HMD at their normal standing eye height.

The blind walking protocol requires subjects to observe a referent object, close (or cover) their eyes, and walk forward. This meant that it was necessary to engineer the HMD frame so that it could swing out of the way (Fig. 5). The frame was attached to one tripod with a caster wheel mount that allowed 360° of rotation, while the other side of the frame rested in an "L" shaped holder. We engineered this apparatus to be stable enough so that, when the HMD was swung out of the way and then back into position, the alignment was preserved as much as possible. During the experiment, we typically only had to make minor adjustments to restore the alignment. We stereo calibrated the display by stereo-aligning a virtual wireframe model of the experimental room to the actual room, and as discussed below, we tested and recalibrated the alignment between the virtual and real referent objects as often as every trial.

We conducted the experiment in two different buildings[4] on the Mississippi State University campus. Location 1 was a 2.28×30.4 meter hallway; observers stood 8.83 meters from one end, and walked down the center of the hallway. Location 2 was an 11.35×7.26 meter empty room in a different building; observers stood 1.7 meters from one wall and faced the long axis of the room. Observers walked down a path that was approximately centered between one wall of the room and a folding wall that extends 2.77 meters into the room. In both locations, we attached a long, flexible measuring tape down the center of the pathway; we used this tape to place the physical referent object at precise distances, and to measure the observer's position during the blind walking trials. The numbers on the tape were much too small to be legible to observers during experimental trials.

We ran the experiment on a Pentium M 1.80 GHz laptop computer with an NVIDIA GeForce FX Go5200 graphics card, which outputs frame-sequential stereo. We monitored the experiment's progress on the laptop screen. We implemented our experimental control code in C++, using the OpenGL library, and Perl.

4.2 Variables and Design

4.2.1 Independent Variables

Observers: We recruited 16 observers from a population of university students (undergraduate and graduate), and staff. Nine of the observers were male, seven were female;

4. Although it was not our desire to change locations during the experiment, we were forced to by two factors: 1) the halogen lights, a lack of air conditioning, and the onset of summer resulted in uncomfortable conditions in Location 1, and 2) the Institute for Neurocognitive Science and Technology, where we conducted this experiment, moved into a new building (Location 2), which meant we had to move our equipment as well. In Section 4.2.3, we discuss where this location change fell in the experimental design.

TABLE 2
Independent Variables and Levels, and Dependent Variables, for Experiment II

INDEPENDENT VARIABLES		
observer	16	(random variable)
environment	4	real world, real + HMD real + virtual + HMD virtual + HMD
protocol	2	blind walking verbal report
distance	3	3, 5, 7 meters
repetition	4	1, 2, 3, 4
DEPENDENT VARIABLES		
judged distance	measured from each *protocol*, *meters*	
error	*judged distance* – *distance*, *meters*	

they ranged in age from 20 to 33, with a mean age of 25.4. We screened the observers, via self-reporting, for color blindness and visual acuity. All observers volunteered, and were compensated $10 per hour for their time. Observers spent an average of 2.25 hours completing the experiment.

Environment: As shown in Table 2 and Fig. 5, observers judged the depth of referents presented in four different environments. In the *real-world* environment, observers saw the real-world referent object, and did not look through the HMD. We included this as a control condition, as it duplicates the setup of distance perception studies with real-world referents [21]. In the $real + HMD$ environment, observers saw the real-world referent object, but this time regarded the referent object through the HMD. In the $real + virtual + HMD$ environment, observers saw the real-world referent object and the virtual referent object at the same time. As discussed below, we carefully calibrated the display so that the two aligned with a high degree of precision. In the $virtual + HMD$ environment, observers saw only the virtual referent object.

Protocol: Observers used two different protocols to judge the depth of referent objects. When using the *blind walking* protocol, observers regarded the referent object for as long as they wished (typically a few seconds), closed their eyes, and then verbally notified the experimenter that they were ready to respond. An experimenter swung the HMD out of the way and said "walk forward"; this operation typically took ~ 2 seconds. After hearing "walk forward," observers walked, with their eyes closed, to their remembered location of the referent object. For environments where a physical referent object was present, a second experimenter removed the object before the observer reached the location. After stopping, observers stood and looked ahead (not down), while the two experimenters silently recorded their distance from the floor-mounted tape. When this was recorded, observers walked to an isolation area, which was a room off of the hallway (Location 1), or an area separated by a folding wall (Location 2). In the isolation area, observers could not see the experimental room. While the observer was gone, the experimenters reset the HMD, set the physical referent to the next distance, and checked and adjusted the HMD calibration. When all was ready, the experimenters asked the observer to return to the starting position without looking at the room, and begin the next trial. During real world environment trials, observers did not look through the HMD. Instead, after the observer closed their eyes, the experimenter waited ~ 2 seconds, and then said "walk forward."

When using the *verbal report* protocol, observers regarded the referent object for as long as they wished (typically a few seconds), and then reported the distance, in whatever units the observer desired. Observers then moved to the isolation area while the experimenters readied everything for the next trial. When all was ready, the experimenters asked the observer to return to the starting position without looking at the room, and begin the next trial. Although the calibration was checked every trial, because the HMD was not swung out of the way, it was generally only necessary to adjust it at the beginning of each block of verbal report trials.

Distance: For *experimental trials*, observers saw referent objects placed at distances of 3, 5, and 7 meters. Because observers may notice the repetition in such a small set of distances, and this can influence their distance judgments (especially verbal reports), 25 percent of the distance judgments were *noise trials*. For these trials, distances were randomly chosen from 0.25-meter increments in the 3 to 7 meter range; the experimenters recorded the data from the noise trials using the same procedures that were used for the experimental trials. The noise trials are not analyzed in this paper.

Repetition: Observers saw four repetitions of each combination of the other independent variables.

4.2.2 Dependent Variables

As shown in Table 2, the primary dependent variable was *judged distance*, which was either measured from the observer's foot position (blind walking), or verbally reported by the observer. We also calculated *error*, which has the same meaning as it did in Experiment I: an *error* close to 0 indicates an accurately judged distance, an $error > 0$ indicates an overestimated judged distance, and an $error < 0$ indicates an underestimated judged distance.

4.2.3 Experimental Design

We used a factorial nesting of independent variables in our within-subjects experimental design. Table 3 shows the loop that our experimental control program used to present the

TABLE 3
Stimulus Presentation Loop and Counterbalancing

PRESENTATION LOOP	LEVELS	ORDER CONTROL
for each *environment*	4	4×4 Latin Square
for each *protocol*	2	2×2 Latin Square
for *distance* ⊗ *repetition* + *noise*	(3 × 4) + 4	Restricted random permutation
present trial		

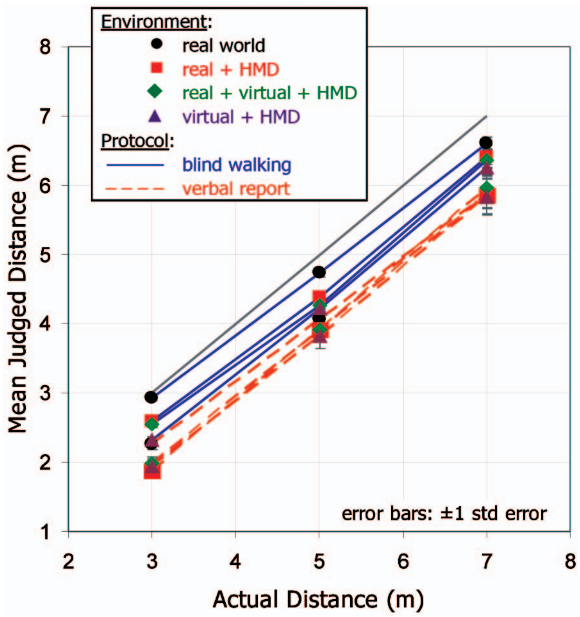


Fig. 6. The main results, plotted as judged distance versus actual referent distance ($N = 1,536$). The light gray line indicates veridical performance.

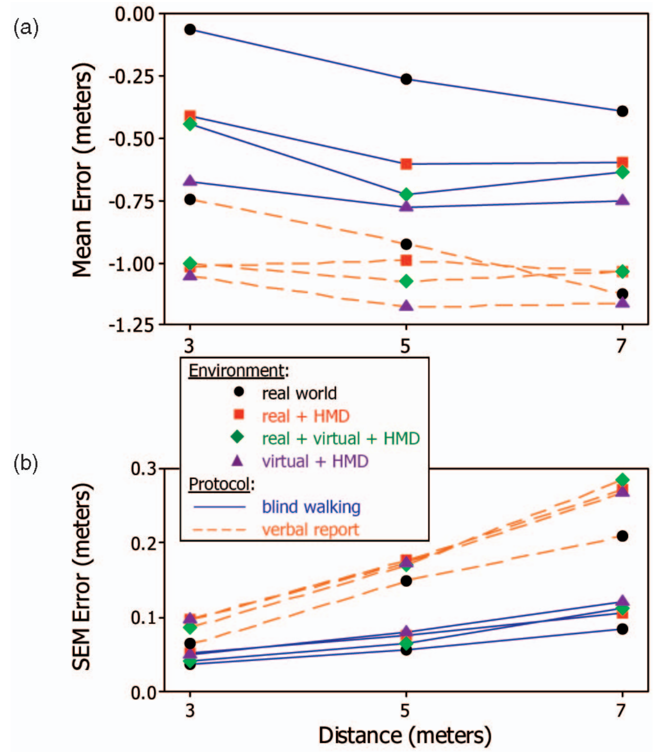


Fig. 7. The main results, plotted as (a) mean error ($N = 1,536$), and (b) standard error of the mean (SEM) error ($N = 1,536$), for each referent distance.

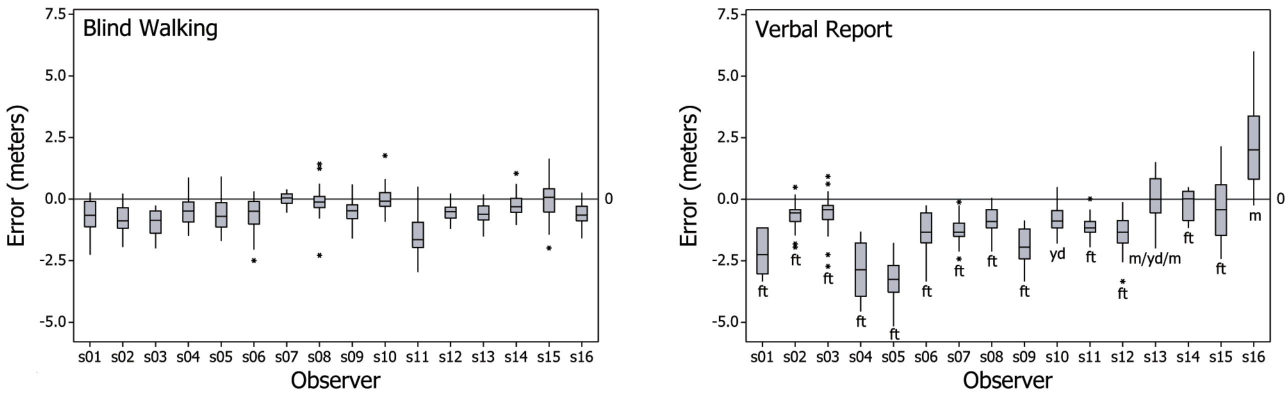
independent variables to the observers. *Environment* varied the slowest; within each environment observers saw each *protocol*. The presentation order of *environment* was controlled by a 4×4 between-subjects Latin Square, while the presentation order of *protocol* was controlled by a 2×2 between-subjects Latin Square; when combined, these two Latin Squares resulted in a presentation order design that repeated modulo eight subjects. Within each $environment \otimes protocol$ block, our control program generated a list of $3\ (distance) \times 4\ (repetition) = 12$ experimental distances, and then added four random *noise* distances. The program then randomly permuted the presentation order of the resulting 16 distances, with the restriction that the same distance could not show up twice in a row. We collected a total of 1,536 data points (16 observers × four environments × two protocols × three distances × four repetitions). As discussed above, the 16 observers participated in two different locations. Observers 1-8 participated in Location 1, while observers 9-16 participated in Location 2. Therefore, the experiment was counterbalanced with respect to the presentation order of the data collected in each location.

4.3 Results and Discussion

4.3.1 Descriptive Results

Fig. 6 shows the main results from the study, which by the convention established in much of the recent VR depth perception literature, is displayed as a correlation between the actual distance and the judged distance. This shows that, like virtual environments presented in opaque HMDs, there is a general trend of egocentric distance underestimation for virtual objects presented in transparent, AR HMDs. The judged distances fell into three main groups, which are listed here along with their mean percentages of actual distance ($percentage = judged\ distance/actual\ distance$): 1) blind walking in the real-world environment: 96 percent, 2) blind walking in the HMD environments, which includes the real-world seen through the HMD: 86 percent, and 3) verbal report: 77 percent. These results can be compared to the percentages from six studies of virtual environment distance perception that examined a similar range of distances with open-loop action-based protocols, as reported by Thompson et al. [34]. These studies reported real-world judgments that ranged from 92-100 percent of actual distances, and virtual environment judgments that ranged from 42-85 percent of actual distances. Our control condition (blind walking in the real-world) had results (96 percent) that are similar to what has been reported across these studies (92-100 percent), and we interpret this as some assurance that our implementation of the blind walking protocol was essentially correct. However, others have achieved results very close to 100 percent [33], and it seems likely that further improvements are possible. More interestingly, we found that the degree of underestimation for the HMD environments (86 percent) is on the low end of what has been observed for virtual environments (42-85 percent).

The rest of the graphs in this paper show results in terms of *error* (Table 2); this metric allows differences in judged distances to be more clearly plotted. Fig. 7a gives the main results in terms of mean *error*. As discussed above, these indicate that all blind walking conditions had less underestimation than verbal report conditions, and that blind walking in the real world was the most accurate of all. In Section 4.3.3 below, we analyze the blind walking results in more detail. Fig. 7b gives the variability of the main results, expressed in terms of the standard error of *error*. These results indicate that as the degree of underestimation increases, so does the variability and, thus, the verbal report results are more variable than the blind walking results. In addition, similar to Experiment I, variability



(a) (b)

Fig. 8. Boxplots showing the error results for each observer. (a) The blind walking results ($N = 768$). (b) The verbal report results ($N = 768$). These are labeled with the units that the observers used: *ft*: feet, *yd*: yards, and *m*: meters. Observer *s*13 began using meters, then switched to yards, and then back to meters. Asterisks "$*$" indicate single outlying data points.

increased with increasing distance, which we generally expect because observer responses are based on depth cues of linearly decreasing effectiveness (i.e., observers are following Weber's law [31]). Finally, there appears to be an increase in gain as well as a bias shift for verbal report, relative to blind walking.

Fig. 8 shows the results for each observer, separated according to protocol. Observers were consistent with blind walking (Fig. 8a), as compared to verbal estimation (Fig. 8b). Observer *s*07 gave extremely consistent blind walking results; this subject reported walking and running on a treadmill with their eyes closed on a regular basis. Observer *s*11, who gave the most underestimated blind walking results, reported being quite fatigued. As indicated in Fig. 8b, observers displayed much more variability with verbal estimation. This variability is also reflected in Fig. 7b, but Fig. 8b shows that most of the extra variability of verbal estimation comes from between-subject differences. When drawing graphs in the style of Fig. 7a, we found that dropping individual observers with high verbal estimation variability (such as *s*05, *s*16, etc.) substantially changed the verbal estimation lines (dotted orange), while the blind walking means (solid blue) were relatively stable. Because of this variability, we do not have much faith in the verbal estimation results, and we do not inferentially analyze them below.

Therefore, in this experiment, the verbal report protocol did not prove itself to be very useful. While some researchers have reached the same conclusion (Jerome and Witmer [14]), others have found a high correlation between open-loop action-based tasks and verbal report (e.g., Loomis and Knapp [21]). It is possible that we could modify the protocol to reduce the noise; for example, we could have used a modified magnitude estimation procedure where observers state their unit of preference (feet, yards, meters, etc.) ahead of time, and then present a 1-unit example stimulus in their field of view, such as a one-foot ruler, or yardstick, or meterstick.

4.3.2 Analysis Techniques

In this section, we describe how we statistically analyzed our results. In addition to the typical ANOVA analysis, we also subjected the results to a *power analysis*, and the techniques for doing this are described in some detail here. Although some of this material is tutorial in nature, the power analysis discussion has two benefits: 1) it shows how to compute *standardized effect sizes* for most of the previously reported studies in the depth perception literature, and 2) it illustrates how to compute a *null hypothesis confidence interval*, which is the statistically proper technique for arguing the truth of a null hypothesis. To date, we have not encountered a discussion of these techniques in the depth perception literature.

We analyzed our results with univariate analysis of variance (ANOVA); these results are given in Table 4. With ANOVA, we modeled our experiment as a repeated-measures design that considers *observer* a random variable and all other independent variables as fixed (Table 2). The distributions on which ANOVA analysis is based assume that, for each tested effect, the data is normally distributed and the variance is homogenous. For repeated-measures designs such as the ones we report here, these two assumptions are jointly referred to as *sphericity* of the variance/covariance matrix. Sphericity is usually violated [3], [12], and Fig. 7b indicates that it is likely violated in this study, at least across protocol and distance. Therefore, following the recommendations of Howell [12, p. 486] and Buchner et al. [3], for each tested effect we applied the Huynh and Feldt correction ε (Table 4). Instead of the standard F-test on n, d degrees of freedom, where n is the numerator and d the denominator of the F ratio, under this correction we calculate the F-test on εn, εd degrees of freedom. This results in a more conservative test, which corrects for the degree to which sphericity is violated.

In addition to significance testing, in this analysis, we also performed two types of *power analysis* (Cohen [4]): 1) *post-hoc power analysis* and 2) establishing *null hypothesis confidence intervals*. Standard significance testing is based on comparing the calculated p value to α, and rejecting the null hypothesis when $p < \alpha$. Typically, and in this study, $\alpha = 0.05$. α is the probability of committing a Type I error (finding an effect when no effect is present in the data [12]); minimizing this error is why α is set to a small number.

TABLE 4
ANOVA Results for Experiment II

Effect	On	N	ε	n	d	F	p	f^2	r	λ	power
1 Environment ***	all data	1536	0.98	3	45	5.89	0.002	0.39	0.65	49.4	1.00
2 Repetition ***	all data	1536	0.89	3	45	18.75	< .000	1.25	0.74	192.8	1.00
3 Environment ***	blind	768	1.00	3	45	12.54	< .000	0.84	0.38	61.1	1.00
4 Environment ***	blind, not real world, 3 meters	192	1.00	2	30	9.38	0.001	0.63	0.51	38.5	1.00
5 Environment (null)	blind, real+HMD and real+virtual+HMD, 3 meters	128	1.00	1	15	0.28	0.604	0.02	0.51	0.6	0.11
6	Null hypothesis confidence interval		1.00	1	15			0.30	0.50	9.0	0.80
7 Environment (null)	blind, not real world, 5 meters	192	0.78	2	30	1.69	0.208	0.11	0.46	4.9	0.45
8 Environment (null)	blind, not real world, 7 meters	192	1.00	2	30	0.69	0.510	0.05	0.59	3.4	0.33
9	Null hypothesis confidence interval		0.78	2	30			0.26	0.46	11.3	0.81

N is the number of data points analyzed; ε is the Hyunh and Feldt correction; n, d are the numerator, denominator degrees of freedom; F is the value of the ANOVA F-Test; p is the conditional probability of the ANOVA F-Test; f^2 is Cohen's effect size; r is the averaged pair-wise correlation; λ is the noncentrality parameter, and power is post-hoc power.

Power analysis calculates a number typically called *power*; 1-*power* is the probability of committing a Type II error (failing to find an effect when one is actually present). Cohen [4] recommends, and we adopt, a goal of achieving $power \geq 0.80$.

Post-hoc power analysis calculates the power of statistically significant findings. Power is a function of three numbers: n, d, and λ, where n is the numerator and d the denominator of the F ratio, and λ is called the *noncentrality parameter*. For a repeated-measures design such the one in this paper,

$$\lambda = \frac{\varepsilon(S-1)nf^2}{1-r}, \tag{1}$$

where ε is the Huynh and Feldt correction factor described above, S is the number of observers in the study, and r is the averaged pair-wise correlation between the levels of the independent variable of the statistically significant finding. f^2 is a standardized measure of effect size for factorial ANOVA designs. As discussed by Cohen [4],

$$f^2 = \frac{\eta^2}{1-\eta^2}, \tag{2}$$

where η^2 (partial eta-squared) is calculated

$$\eta^2 = \frac{nF}{nF+d}, \tag{3}$$

and n, d, and F are the numerator, denominator, and F value of the F-test.

The value of (2) and (3) is that they allow the standardized effect size f^2 to be calculated from the commonly-reported F-test parameters n, d, and F. For example, the effect in Table 4, line 1, would typically be reported $F(3,45) = 5.89$, $p = .002$; here, $n = 3$, $d = 45$, $F = 5.89$ and (2) and (3) give $f^2 = 0.39$. This allows effect sizes to be computed and compared with previous studies that do not directly report f^2, and most of the studies reported in the depth perception literature give F-tests for important findings. However, (1) shows that λ is a function of ε, S, n, f^2, and r, and while the number of observers S is typically reported, values for ε and r are typically not. Therefore, it is generally not possible to directly compute the power of previously reported repeated-measures designs. Most of the previous studies in the depth perception literature are repeated-measures designs, because the tested distances are usually measured multiple times for each observer, although other variables often vary between observers. For Experiment II, Table 4 gives the values of all of these parameters, as well as the resulting post-hoc power, for each significant effect discussed in the next section. We used G*Power [3] and SPSS to calculate power.

When a finding is not statistically significant (e.g., when $p \geq 0.05$), power analysis can be used to establish a *null hypothesis confidence interval*. In general, a large p value cannot establish the truth of the null hypothesis, because the null hypothesis is a point result (Howell [12]). However, power analysis can bound the possible effect size f^2 to lie within a confidence interval. If the resulting interval is small enough, then the null hypothesis has effectively been argued. Establishing such an interval requires assuming values for the parameters ε, n, d, f^2, and r. In Table 4, lines 6 and 9 list the parameter values that we assumed to establish null hypothesis confidence intervals. In all cases, we chose our parameters to be conservative population estimates, based on the parameter values in the rest of Table 4.

4.3.3 Inferential Results

In this section, when we discuss hypothesis tests, we also give the Table 4 line number that lists the additional parameters. There was a main effect over all of the data ($N = 1{,}536$ data points) of environment ($F(3,45) = 5.89$, $p = .002$, line 1), which is explored in more detail below. There was also an effect of repetition ($F(3,45) = 18.75$, $p < .000$, line 2); observers increased their accuracy with repeated exposure to each condition. This repetition effect also appeared in most of the ANOVAs of subsets of the data that are reported below, but we do not further consider it.

Fig. 9 shows the blind walking error means and standard errors from Figs. 7a and 7b. Within the blind walking data ($N = 768$), there was an effect of environment ($F(3,45) = 12.54$, $p < .000$, line 3). The standard error bars in Fig. 9 indicate that this is due to a separation between the real world condition and the HMD conditions; unsurprisingly, it was easier to judge the distance of the real-world referent. Interestingly, for the nonreal-world conditions $\mathrm{real+HMD}$, $\mathrm{real+virtual+HMD}$, and $\mathrm{virtual+HMD}$, the overlap in the error bars suggests that the HMD conditions were equally difficult at 5 and 7 meters. We investigated this possibility by performing separate ANOVAs on the nonreal world

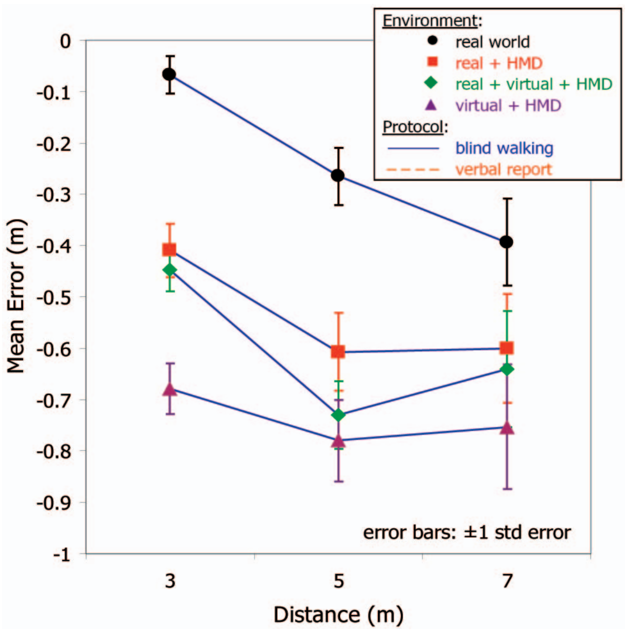


Fig. 9. The mean error results for blind walking $(N = 768)$.

conditions at 3 meters, 5 meters, and 7 meters ($N = 192$ for each test). At 3 meters, as suggested by the separation between the $\mathrm{virtual} + \mathrm{HMD}$ condition and the other two conditions ($\mathrm{real} + \mathrm{HMD}$, $\mathrm{real} + \mathrm{virtual} + \mathrm{HMD}$), there was still an effect of environment ($F(2,30) = 9.38$, $p = .001$, line 4). However, a test on the remaining two conditions ($N = 128$) indicated no effect of environment ($F(1,15) = .28$, $p = .604$, line 5). Furthermore, our experiment could detect effects as small as $f^2 = .30$ with $power = .80$ (line 6), and .30 is small compared to the f^2 sizes of the significant effects just discussed (lines 1-5). At 5 meters, there was no effect of environment for the nonreal-world conditions ($F(2,30) = 1.69$, $p = .208$, line 7), nor was there an effect at 7 meters ($F(2,30) = .69$, $p = .510$, line 8). For either of these distances, our experiment could reliably detect effects as small as $f^2 = .26$ with $power = .80$ (line 9).

The relative accuracy of the real-world (control) condition is not surprising; this has been found by many researchers who have compared real-world referents to virtual environment referents (e.g., Thompson et al. [34]). The interesting aspect of these findings, which is implied by the null confidence intervals just presented, is that the $\mathrm{real} + \mathrm{HMD}$ environment exhibits the same degree of underestimation as both the $\mathrm{real} + \mathrm{virtual} + \mathrm{HMD}$ and $\mathrm{virtual} + \mathrm{HMD}$ environments (with the exception of the $\mathrm{virtual} + \mathrm{HMD}$ environment at 3 meters). We hypothesize that the most likely explanation is a combination of the framing effect of our display's narrow field-of-view, as well as the fact that observers were not free to rotate their heads when looking through the HMD. Although some researchers have hypothesized that a limited HMD field-of-view does not cause distance underestimation (Creem-Regehr et al. [5], Knapp and Loomis [16]), Wu et al. [37] found evidence that it does cause underestimation. However, the field-of-view studied for the negative results was $42^\circ \times 32^\circ$ (horizontal $\times$ vertical) (Creem-Regehr et al.) and $47^\circ \times 36^\circ$ (Knapp and Loomis), while Wu et al. only found underestimation when the field of view was restricted to at least $21.2^\circ \times 21.2^\circ$. Our field-of-view was $27^\circ \times 20^\circ$, which compares to Wu et al.'s vertical dimension. Furthermore, Creem-Regehr et al. found that distances were underestimated when head rotations were prevented, and Wu et al. found that distances were not underestimated with a narrow field-of-view when observers were allowed to scan the ground plane in the near-to-far direction (from their feet to the object). Given the size of our HMD's field-of-view and the fact that our HMD's mounting prevented head rotations, our results are consistent with the findings of both Creem-Regehr et al. and Wu et al.

We noticed that when we looked through the display in the $\mathrm{real} + \mathrm{virtual} + \mathrm{HMD}$ environment, and the real object was pulled away, the virtual object seemed to float up from the ground and move closer to us. We hypothesize that the floating upward effect is caused by a lack of cues suggesting that the virtual objects are attached to the ground, and the movement closer is caused by an inward change in vergence angle,[5] driven by accommodative/vergence mismatch. When the accommodative demand (1.2 meters for our HMD) is closer than the fixation distance (3 to 7 meters in this experiment), the resting vergence angle of the eyes shifts inward, causing objects to be perceived as closer than their actual location (Mon-Williams and Tresilian [25]). In the situation described here, when the real and the virtual object are seen together, the eyes accommodate to the real object, and there is no accommodative/vergence mismatch, but when the real object is pulled away, the mismatch occurs. The greater underestimation of the $\mathrm{virtual} + \mathrm{HMD}$ environment at 3 meters, relative to the $\mathrm{real} + \mathrm{virtual} + \mathrm{HMD}$ and $\mathrm{real} + \mathrm{HMD}$ environments, is consistent with this hypothesis.

5 Conclusions

AR has many compelling applications, but many will not be realized until we understand how to place graphical objects in depth relative to real-world objects. This is difficult because imperfect AR displays and novel AR perceptual situations such as x-ray vision result in conflicting depth cues. Egocentric distance perception in the real world is not yet completely understood (Loomis and Knapp [21]), and its operation in VR is currently an active research area. Even less is known about how egocentric distance perception operates in AR settings; the comprehensive survey in Section 2 found only seven previously published papers describing unique experiments.

To our knowledge, along with Jerome and Witmer [14] and Kirkley [15], we have conducted the first experiments that have measured AR depth judgments at medium and far-field distances, which are important distances for a number of compelling AR applications. Experiment I used a perceptual matching protocol, and studied distances of 5 to 45 meters. It provides evidence for a switch in bias, from underestimating to overestimating distance, at ~ 23 meters (Fig. 2), and provides an initial quantification of how much more difficult the depth judgment task is in the x-ray vision condition (Fig. 3). It also found an effect of height in the

5. Postexperiment, the first three authors used nonius lines to test for changes in vergence angle for this situation, using a technique similar to the one reported by Ellis and Menges [9]. For all three authors, the test indicated an inward change in vergence angle.

visual field in the form of an interaction with repetition (Fig. 4). We suggest that part of this interaction replicates the VR depth underestimation problem, and further suggest that the effect of practice on VR depth underestimation should be explored. Experiment II used blind walking and verbal report protocols, and studied distances of 3 to 7 meters. Experiment II provides evidence that the egocentric depth of AR objects is underestimated at these distances, but to a lesser degree than has previously been found for most virtual reality environments. Furthermore, the results are consistent with previous studies that have implicated a restricted field-of-view, combined with an inability for observers to scan the ground plane in a near-to-far direction, as explanations for the observed depth underestimation.

The perceptual matching protocol used in Experiment I is generally representative of the types of depth estimation tasks we can imagine users performing in an AR-based situational awareness system such as BARS [19]; such tasks might involve estimating or specifying the distance to urban objects such as buildings, personnel, or vehicles, even if the objects are hidden from sight. While we can also imagine users giving a verbal estimate of depth, we cannot imagine BARS users blind walking. However, as Loomis and Knapp [21] discuss, there are compelling theoretical arguments and substantial empirical evidence that depth judgments from open-loop action-based protocols such as blind walking are driven by a relatively pure percept of egocentric distance. However, to achieve this purity, the protocols must be carefully implemented, in order to counteract cognitive techniques such as footstep counting. In contrast, the depth judgments from the perceptual matching protocol are likely primarily driven by minimizing the exocentric distance between the referent and the target objects, although some percept of egocentric depth of the referent may also be involved. So while there is substantial theoretical value in the blind walking protocol, there is also practical value in studying protocols, such as perceptual matching, that are closer to the real-world tasks we imagine AR users actually performing.

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A Perceptual Matching Technique for Depth Judgments in Optical, See-Through Augmented Reality

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Abstract

A fundamental problem in optical, see-through augmented reality (AR) is characterizing how it affects the perception of spatial layout and depth. This problem is important because AR system developers need to both place graphics in arbitrary spatial relationships with real-world objects, and to know that users will perceive them in the same relationships. Furthermore, AR makes possible enhanced perceptual techniques that have no real-world equivalent, such as *x-ray vision*, where AR users are supposed to perceive graphics as being located behind opaque surfaces.

This paper reviews and discusses techniques for measuring egocentric depth judgments in both virtual and augmented environments. It then describes a perceptual matching task and experimental design for measuring egocentric AR depth judgments at medium- and far-field distances of 5 to 45 meters. The experiment studied the effect of field of view, the x-ray vision condition, multiple distances, and practice on the task. The paper relates some of the findings to the well-known problem of depth underestimation in virtual environments, and further reports evidence for a switch in bias, from underestimating to overestimating the distance of AR-presented graphics, at ~23 meters. It also gives a quantification of how much more difficult the x-ray vision condition makes the task, and then concludes with ideas for improving the experimental methodology.

CR Categories: H.5 [**Information Interfaces and Presentation**]: H.5.1: Multimedia Information Systems — Artificial, Augmented, and Virtual Realities; H.5.2: User Interfaces — Ergonomics, Evaluation / Methodology, Screen Design

Keywords: Experimentation, Measurement, Performance, Depth Perception, Optical See-Through Augmented Reality

1. Introduction

Optical, see-through augmented reality (AR) is the variant of AR where graphics are superimposed on a user's view of the real world with optical, as opposed to video, combiners. Because optical, see-through AR (simply referred to as "AR" for the rest of this paper) provides direct, heads-up access to information that is correlated with a user's view of the real world, it has the potential to revolutionize the way many tasks are performed. In addition, AR makes possible enhanced perceptual techniques that have no real-world equivalent. One such technique is *x-ray vision*, where AR users perceive objects which are located behind opaque surfaces.

The AR community is applying AR technology to a number of unique and useful applications [1]. The application that motivated the work described here is mobile, outdoor AR for situational awareness in urban settings [10]. This is a very difficult application domain for AR; the biggest challenges are outdoor tracking and registration, outdoor display hardware, and developing appropriate AR display and interaction techniques.

In this paper we are focused on AR display techniques, in particular how to correctly display and accurately convey depth. This is a hard problem for several reasons. Current head-mounted displays are compromised in their ability to display depth — for example, they often dictate a fixed accommodative focal depth. Furthermore, it is well known that distances are persistently underestimated in VR scenes depicted in head-mounted displays [3, 8, 12, 14, 17, 22, 25, 26], but the reasons for this phenomenon are not yet clear. In addition, unlike virtual reality, with AR users see the real world, and therefore graphics need to appear to be at the same depth as co-located real-world objects, even though the graphics are physically drawn directly in front of the eyes. Furthermore, there is no real-world equivalent to x-ray vision, and it is not yet understood how the human visual system reacts to information displayed with purposely conflicting depth cues, where the depth conflict itself communicates useful information. In the work reported in this paper, our larger goal was to study AR depth perception, and our specific goal was to develop an experimental methodology for measuring AR depth judgments at medium- and far-field distances.

2. Background and Related Work

Depth Cues and Cue Theory: Human depth perception delivers a vivid three-dimensional perceptual world from flat, two-dimensional, ambiguous retinal images of the scene. Current thinking on how the human visual system is able to achieve this performance emphasizes the use of multiple *depth cues,* available in the scene, that are able to resolve and disambiguate depth relationships into reliable, stable percepts. *Cue theory* describes how and in which circumstances multiple depth cues interact and combine [9]. Generally, ten depth cues are recognized [7]: (1) binocular disparity, (2) binocular convergence, (3) accommodative fo-

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cus, (4) atmospheric haze, (5) motion parallax, (6) linear perspective and foreshortening, (7) occlusion, (8) height in the visual field, (9) shading, and (10) texture gradient. Real-world scenes combine some or all of these cues, with the structure of the scene determining the salience of each cue. Although *depth cue interaction* models exist, these were largely developed to account for how stable percepts could arise from a variety of cues with differing salience. The central challenge in understanding human depth perception in AR is determining how stable percepts can arise from inconsistent, sparse, or conflicting depth cues, which arise either from imperfect AR displays, or from novel AR perceptual situations such as x-ray vision. Therefore, models of AR depth perception will likely inform both AR technology, as well as depth cue interaction models.

NEAR-, MEDIUM-, AND FAR-FIELD DISTANCES: Depth cues vary both in their salience across real-world scenes, and in their effectiveness by distance. Cutting [2] has provided a useful taxonomy and formulation of depth cue effectiveness by distances that relate to human action. He divided perceptual space into three distinct regions, which we term near-field, medium-field, and far-field. The *near field* extends to about 1.5 meters: it extends slightly beyond arm's reach, it is the distance within which the hands can easily manipulate objects, and within this distance, depth perception operates almost veridically. The *medium field* extends from about 1.5 meters to about 30 meters: it is the distance within which conversations can be held and objects thrown with reasonable accuracy; within this distance, depth perception for stationary observers becomes somewhat *compressed* (items appear closer than they really are). The *far field* extends from about 30 meters to infinity, and as distance increases depth perception becomes increasingly compressed. Within each of these regions, different combinations of depth cues are available.

EGOCENTRIC DISTANCE JUDGMENT TECHNIQUES: In the development of AR (and VR) environments, we are interested in measuring the perception of distance, but we suffer from the classic problem that perception is an invisible cognitive state, and so we have to find something measurable which can be theoretically related to the perception of distance. Therefore, we devise experiments where we measure distance *judgments*, and then infer distance perception from these judgments. The most general categorization of the judgments we can measure is ego- or exocentric: *egocentric* distances are measured from an observer's own view point, while *exocentric* distances are measured between different objects in a scene. Loomis and Knapp [12] and Foley [5] review and discuss the methods that have been developed to measure judged egocentric distances.

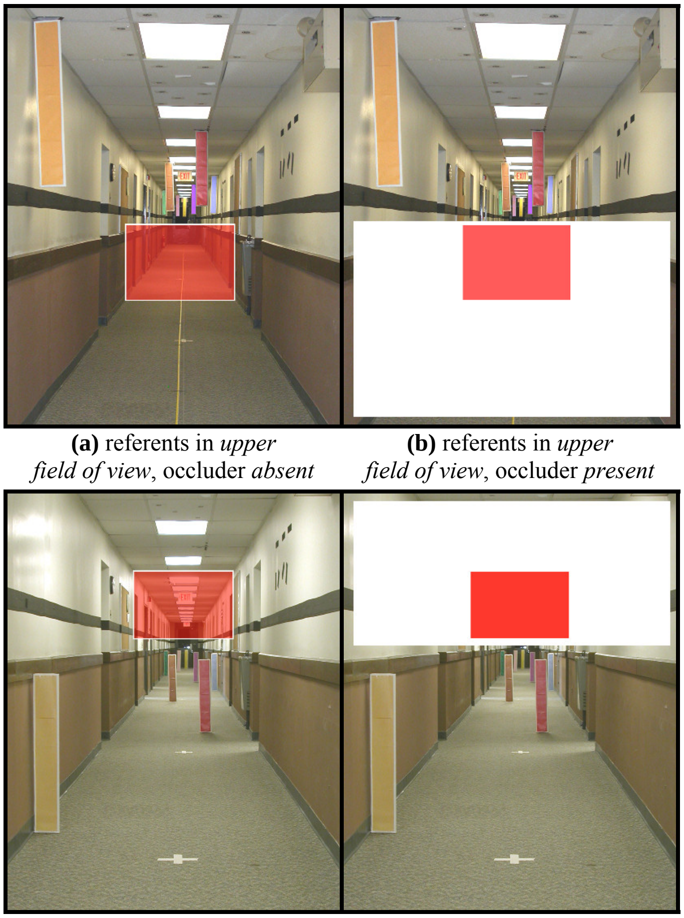
There have been three primary methods: *verbal report*, *perceptual matching*, and *open-loop action-based tasks*. With *verbal report* [5, 8, 12, 14] observers verbally estimate the distance to an object, typically using whatever units they are most familiar with (e.g., feet, meters, or multiples of some given referent distance). Observers have also verbally estimated the size of familiar objects [12], which are then used to compute perceived distance. *Perceptual matching* tasks [4, 5, 13, 19, 26] involve the observer adjusting the position of a target object until it perceptually matches the distance to a referent object. Perceptual matching is an example of an *action-based task*; these tasks involve a physical action on the part of the observer that indicates perceived distance. Action-based tasks can be further categorized into open- and closed-loop tasks. In an *open-loop* task, observers do not receive any visual feedback as they perform the action, while in a *closed-loop* task they do receive feedback. By definition, perceptual matching tasks are closed-loop action-based tasks.

A wide variety of *open-loop action-based tasks* have been employed. For all of these tasks, observers perceive the egocentric distance to an object, and then perform the task without visual feedback. A common open-loop action-based task has been *visually directed walking* [3, 8, 12, 14, 25, 26], where observers perceive an object at a certain distance, and then cover their eyes and walk until they believe they are at the object's location. Visually directed walking has been found to be very accurate for distances up to 20 meters [12], and has been widely used to study egocentric depth perception at medium- and far-field distances in both real-world and VR settings. A closely related technique is *imagined visually directed walking* [17], where observers close their eyes and imagine walking to an object while starting and stopping a stopwatch; the distance is then computed by multiplying the time by the observers' normal walking speed. Yet another variant is *triangulation by walking* [12, 22, 25], where observers view an object, cover their eyes, walk a certain distance in a direction oblique to the original line of sight, and then indicate the direction of the remembered object location; their perception of the object's distance can then be recovered by simple trigonometric calculations. Near-field distances have been studied by *open-loop pointing* tasks [5, 15], where observers indicate distance with a finger or manipulated slider that is hidden from view.

In addition, some researchers have used *forced-choice* tasks [11, 18, 19] to study egocentric depth perception. In forced-choice tasks observers make one of a small number of discrete depth judgment choices, such as whether one object is closer or farther than another; or at the same or a different depth; or at a near, medium, or far depth, etc. These tasks tend to use a large number of repetitions for a small number of observers, and can employ psychophysical techniques to measure and analyze the judged depth [18, 19].

THE VIRTUAL REALITY DEPTH UNDERESTIMATION PROBLEM: Over the past several years many studies have examined egocentric depth perception in VR environments. A consistent finding has been that *egocentric depth is underestimated* when objects are viewed on the ground plane, at near- to medium-field distances, and the VR environment is presented in a head-mounted display (HMD) [3, 8, 12, 14, 17, 22, 25, 26]. As discussed above, most of these studies have utilized open-loop action-based tasks, although the effect has been observed with perceptual matching tasks as well [26]. These studies have examined various theories as to why egocentric depth is underestimated, and have found evidence that underestimation is caused by an HMD's limited field-of-view [26]; that underestimation is *not* caused by an HMD's limited field-of-view [3, 8]; that the weight of the HMD itself might contribute to the phenomenon [25]; that monocular versus stereo viewing does not cause it [3]; that the quality of the rendered graphics does not cause it [22]; that the effect persists even when observers see live video of the real world in an HMD [14]; and that the effect might exist when VR is displayed on a large-format display screen as well [17]. In summary, the egocentric distance underestimation effect is real, and although its parameters are being explored, it is not yet fully understood.

PREVIOUS AR DEPTH JUDGMENT STUDIES: There have been a small number of studies that have examined depth judgments with optical, see-through AR displays. Ellis and Menges [4] summarize a series of AR depth judgment experiments, which used a perceptual matching task to examine near-field distances of 0.4 to 1.0 meters, and studied an occluding surface (the x-ray vision



(a) referents in *upper field of view*, occluder *absent*
(b) referents in *upper field of view*, occluder *present*
(c) referents in *lower field of view*, occluder *absent*
(d) referents in *lower field of view*, occluder *present*

Figure 1: The experimental setting and layout of the real-world referents and the virtual target rectangle. Observers manipulated the depth of the target rectangle to match the depth of the real-world referent with the same color (red in this example). Note that these images are not photographs taken through the actual AR display, but instead are accurate illustrations of what observers saw.

condition), convergence, accommodation, observer age, and monocular, biocular, and stereo AR displays. They found that monocular viewing degraded the depth judgment, and that the x-ray vision condition caused a change in vergence angle which resulted in depth judgments being biased towards the observer. They also found that cutting a hole in the occluding surface, which made the depth of the virtual object physically plausible, reduced the depth judgment bias. McCandless et al. [13] used the same experimental setup and task to additionally study motion parallax and AR system latency in monocular viewing conditions; they found that depth judgment errors increased systematically with increasing distance and latency. Rolland et al. [18], in addition to a substantial treatment of AR calibration issues, discuss a pilot study at near-field distances of 0.8 to 1.2 meters, which examined depth judgments of real and virtual objects using a forced-choice task. They found that the depth of virtual objects was overestimated at the tested distances. Rolland et al. [19] then ran additional experiments with an improved AR display, which further examined the 0.8 meter distance, and compared forced-choice and perceptual matching tasks. They found improved depth accuracy and no consistent depth judgment biases. Livingston et al. [11] discuss an experiment that used a forced-choice task to examine graphical parameters such as drawing style, intensity, and opacity on occluded AR objects at far-field distances of 60 to 500 meters. They found that certain parameter settings were more effective for their task.

3. AR Depth Experiment

We developed a perceptual matching technique for measuring AR depth judgments. As we developed our experimental protocol, setting, and task, we pursued the following design goals:

- Study medium- and far-field distances, which interest us because they have not been well-studied in AR, different depth cues operate at these distances, and these distances are meaningful in our application domain [10]. We studied distances between 5.25 and 44.31 meters.
- Compare the occluded (x-ray vision) condition to the non-occluded condition.
- Require observers to simultaneously attend to the real world and virtual objects in order to correctly perform the task. This addresses a criticism of some previous AR studies [6, 11], where observers could essentially ignore the real world and yet still perform the task.
- Ensure that our task is not 2D solvable, but requires a depth judgment to correctly perform. A *2D solvable* task can be solved by only attending to 2D geometry. For example, if we used height in the visual field to encode the depth of two virtual objects, and then asked observers which one was farther, they could correctly answer by simply noting which had the greater 2D y-coordinate.
- Control the ratio of environmental illumination to AR display brightness. Even though our application domain calls for using AR outdoors, we needed to control this ratio because our AR system and display cannot adjust to or match outdoor illuminance values [6]. Therefore, we found an indoor space (a hallway) that was large enough to study medium- and far-field distances, and we covered the windows with thick black felt.

3.1 Experimental Task

We measured depth judgments with a perceptual matching task. Figure 1 shows the experimental setting. We seated observers on a tall stool 3.4 meters from one end of a 50.1-meter long hallway. Observers looked down the hallway, through an optical, see-through AR display mounted on a frame. We mounted the display so the center of each lens was 147.3 cm above the floor, and we adjusted the height of the stool so that observers could comfortably look through the display. Because the display was rigidly mounted, each observer saw exactly the same field-of-view. Observers saw a series of eight real-world *referents*, approximately positioned evenly down the hallway (Figure 1). Each referent was a different color. The AR display showed a virtual *target*, which we drew as a semi-transparent rectangle that horizontally filled the hallway, and vertically extended about half of the hallway's height. We utilized a rectangular target because our application domain [10] involves the AR presentation of rectangular building elements, such as hallways and doorways. Observers placed their right hand on a trackball; by rolling the trackball forwards and backwards, they moved the target in depth up and down the hallway.

For each trial, our software drew the target rectangle at a random initial depth position; it drew the target rectangle with a

Table 1: Independent and dependent variables.

<table>
<tr><th colspan="5">INDEPENDENT VARIABLES</th></tr>
<tr><td>observer</td><td>8</td><td colspan="3">(random variable)</td></tr>
<tr><td>(referent) field of view</td><td>2</td><td colspan="3">upper, lower</td></tr>
<tr><td>occluder</td><td>2</td><td colspan="3">present, absent</td></tr>
<tr><td rowspan="9">distance</td><td rowspan="9">8</td><td>DISTANCE (METERS)</td><td>ANGULAR SIZE (° VISUAL ANGLE)</td><td>COLOR</td></tr>
<tr><td>5.25</td><td>1.75</td><td>orange</td></tr>
<tr><td>11.34</td><td>.808</td><td>red</td></tr>
<tr><td>17.42</td><td>.526</td><td>brown</td></tr>
<tr><td>22.26</td><td>.412</td><td>blue</td></tr>
<tr><td>27.69</td><td>.331</td><td>purple</td></tr>
<tr><td>33.34</td><td>.275</td><td>green</td></tr>
<tr><td>38.93</td><td>.235</td><td>pink</td></tr>
<tr><td>44.31</td><td>.206</td><td>yellow</td></tr>
<tr><td>repetition</td><td>10</td><td colspan="3">1, 2, 3, 4, 5, 6, 7, 8, 9, 10</td></tr>
<tr><th colspan="5">DEPENDENT VARIABLES</th></tr>
<tr><td>absolute error</td><td colspan="4">| judged distance – actual distance |, meters</td></tr>
<tr><td>signed error</td><td colspan="4">judged distance – actual distance, meters
+: observer overestimated target distance
–: observer underestimated target distance</td></tr>
</table>

white border, and colored the target interior to match the color of one of the referents (Figure 1). The software smoothly modulated the opacity of the color according to distance: close to the observer the color was more opaque, and it grew progressively more transparent with increasing distance. This was in addition to the transparency of the graphics induced by the AR display; Livingston et al. [11] previously determined this to be an effective graphical technique for distance encoding, which approximates the depth cue of atmospheric haze. The software also printed a text label that named the color at the bottom of the display screen. The observer's task was to adjust the target's depth position until it matched the depth of the referent with the same color (Figure 1). When the observer believed the target depth matched the referent depth, they pressed a mouse button on the side of the trackball. This made the target disappear; the display then remained blank for approximately one second, and then the next trial began.

For the display device we used a Sony Glasstron LDI–100B stereo optical see-through display. We increased the display's transparency by removing the LCD opacity filter, and we set the display brightness to its maximum setting. Our Glasstron displays 800 × 600 (horizontal by vertical) pixels in a transparent window which subtends 28.0° × 21.3°[1], and thus each pixel subtends approximately .033° × .033°. This window is approximately centered in a larger semi-transparent frame, which is tinted like sunglasses and so attenuates the brightness of the real world. The outer edge of this frame subtends 63.3° × 39.7°. We stereo calibrated the display by stereo-aligning a rectangle that matched a rectangular window at the far end of the hallway; in Figure 1 this window is covered by heavy black felt and so is not visible. We had to slightly rotate (yaw and pitch) the scene in each eye in order to horizontally and vertically stereo-align the stimuli; we perform this rotation in software. Because the display was rigidly mounted and not tracked, we only had to calibrate the display once; it was not recalibrated on a per-observer basis. We ran the experiment on a Pentium IV 3.06 GHz computer with an Nvidia Quadro4 graphics card, which outputs frame-sequential stereo. We split the video signal, sending one signal to the AR display, and one to a monitor, so we could see the observers' progress. We implemented our experimental control code in Java.

[1] Angular measures in this paper are in degrees of visual arc.

3.2 Variables and Design

3.2.1 Independent Variables

OBSERVERS: We recruited eight observers from a population of scientists and engineers. Seven of the observers were male, one was female; they ranged in age from 21 to 47. We screened the observers, via self-reporting, for color blindness and visual acuity. All observers volunteered and received no compensation.

FIELD OF VIEW: As shown in Figure 1, we placed the referents in the observer's *upper* and *lower* field of view, by mounting the referents either on the ceiling or the floor. Our experimental control program rendered the target in the opposite field of view as the referents. We manipulated field of view in this experiment because we earlier ran a four-observer pilot experiment with the same task, but with the referents exclusively in the lower field of view. The pilot data suggested that observers consistently underestimated target depth, similar to the results that have been found in virtual environments [3, 8, 12, 14, 17, 22, 25, 26]. Wu, Ooi, and He [26] have argued that this effect is caused by a patch of far ground surface, which is actually flat, being perceived as tilted towards the vertical. Tyler [23] found that objects slightly closer in the lower field of view were judged equidistant to objects in the upper field of view. Because our experimental setup (Figure 1) has a ceiling with rich perspective depth cues, we decided to test referents mounted on both the ceiling and the floor. All of the studies which show distance underestimation in virtual environments cited in this paragraph studied referent objects on the ground plane, and hence (using the terminology of this paper) in the observer's lower field of view.

OCCLUDER: As discussed above, we are interested in understanding AR depth perception in the x-ray vision condition. When the *occluder* was *absent* (Figure 1, (a) and (c)), observers could see the hallway behind the target. When the *occluder* was *present* (Figure 1, (b) and (d)), we mounted a heavy rectangle of foamcore posterboard across the observer's field-of-view, which occluded the view of the hallway behind the target. We carefully positioned the occluder so that it did not cut off the observer's view of the bottom (top) of the referents, and yet so it fully occluded the target throughout the entire possible depth range.

Because the hallway's linear perspective becomes quite compressed at 50 meters, we had to calibrate the position of the occluder and the display. In fact, the tightness of this positioning was our original motivation for rigidly mounting the display: without it, observers could easily look over (or under) the occluder to see an unoccluded view of the target, by moving their head up or down only a few centimeters. In addition, our hallway contains a dark, wooden molding between the brown-colored lower walls and the cream-colored upper walls (Figure 1). In the occluded condition, when the referents were in the lower field of view (Figure 1 (d)), this molding formed a strong linear perspective cue that was missing when the field of view was reversed (Figure 1 (b)). Therefore, we carefully positioned and applied black gaffer's tape to the upper walls, which yielded a comparable linear perspective cue in both field of view conditions.

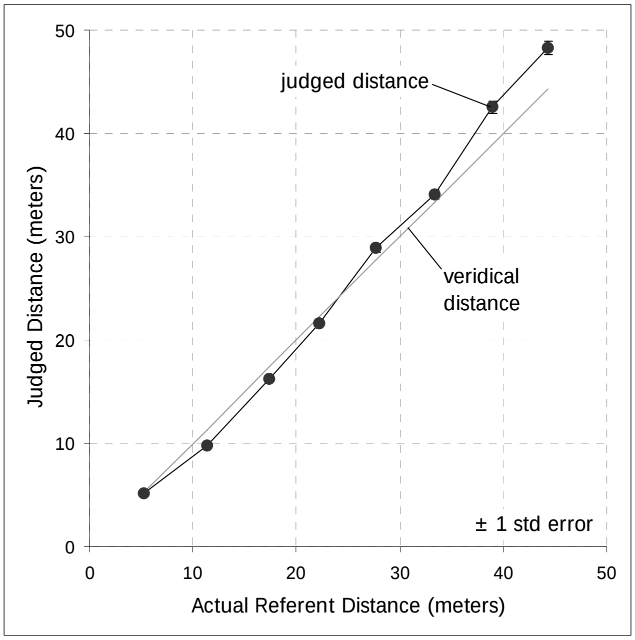


Figure 2: The main result, plotted as judged distance versus actual referent distance. The light grey line indicates veridical performance. For this and all figures, absent error bars indicate the standard error is smaller than the symbol size.

REFERENT DISTANCE: We placed the eight referents at the distances from the observer indicated in Table 1; these distances are measured from the front of the Glasstron AR display. We positioned the referents left and right in the visual field so that they were all visible from the observer's position. As indicated in Figure 1, we placed three of the referents adjacent to a wall and the last referent in the very center; we slightly offset the remaining four referents from the center. The width of the referents subtended from 1.75° to .206°; the farthest referent was over 12 times wider than the standard limit of visual acuity of about 1 minute of visual arc [20]. In person, it was easier to perceive the far referents than it is to see them in Figure 1.

We built the referents out of triangular shipping boxes, which measured 15.3 cm wide by 96.7 cm tall. We covered the boxes with the colors listed in Table 1; these are the eight chromatic colors from the eleven *basic color terms*, which are the colors with one-word English names that Smallman and Boynton [21] have shown to be maximally discriminable and unambiguously named, even cross-culturally (the remaining color terms are 'white', 'black', and 'grey'). We created the colors by printing single-colored sheets of paper with a color printer. To increase the contrast of the referents, we created a border around each color with white gaffer's tape. We affixed the referents to the ceiling and floor with Velcro.

REPETITION: We presented each combination of the other independent variables 10 times.

3.2.2 Dependent Variables

For each trial, observers manipulated a trackball to place the target at their desired depth down the hallway, and pressed the trackball's button when they were satisfied. The trackball produced 2D cursor coordinates, and we converted the *y*-coordinate into a depth value with the perspective transform of our graphics pipeline; we used this depth value to render the target rectangle. When an observer pressed the mouse button, we recorded this depth value as the observer's *judged distance*. As indicated in Table 1, we used the judged distance to calculate two dependent variables, *absolute error* and *signed error*.

3.2.3 Experimental Design and Procedure

We used a factorial nesting of independent variables for our experimental design, which varied in the order they are listed in Table 1, from slowest (observer) to fastest (repetition). We collected a total of 2560 data points (8 observers * 2 fields of view * 2 occluder states * 8 distances * 10 repetitions). We counterbalanced presentation order with a combination of Latin squares and random permutations. Each observer saw all levels of each independent variable, so all variables were within-subject.

Each observer first read and signed a consent form, and then took a stereo acuity test, which all observers passed. The observer next completed 5 practice trials, which used a clear, colorless target rectangle that was only perceptible because of its white border; we verbally asked the observer to place the target on random referents until we felt that the observer understood the task. The observer next completed four blocks of 80 trials each. Between blocks the observer rested for as long as they desired, but at least long enough for us to either mount or dismount the occluder, and to move all of the referents from the floor to the ceiling or vice versa. The entire procedure took from 60 to 90 minutes to complete.

3.3 Results

We analyzed our results with analysis of variance (ANOVA) and regression analysis. With ANOVA we modeled our experiment as a repeated-measures design that considers *observer* a random variable and all other independent variables as fixed (Table 1). This type of design factors out between-subject differences; it allows greater sensitivity for detecting experimental effects with fewer observers, but at the cost of not allowing us to examine individual differences. Eight observers allowed us to detect main effects as small as 1.04 meters for signed error (N = 1280, *power* = 95%, α = 5%, σ = 7.27 meters) and .79 meters for absolute error (N = 1280, *power* = 95%, α = 5%, σ = 5.55 meters), and these effect sizes are small compared to the effects discussed in this section. Therefore, eight observers was an adequate number of subjects for this study.

When deciding which results to report, in addition to considering the p value, the standard measure of *effect significance*, we also considered η^2 (eta-squared), a standard measure of *effect size*. η^2 is an approximate measure of the percentage of the observed variance that can be explained by a particular effect, and is an appropriate effect size measure for a non-additive repeated-measures design [24].

Figure 2 summarizes the main experimental results, which by convention is given as a correlation between the actual referent distances and the judged distances. Theoretically perfect (veridical) performance is indicated by the diagonal line. The data indicate distance underestimation for referents 2, 3, and 4, followed by increasing distance overestimation. This trend is analyzed in more detail below.

Figure 3(a) shows that the variability (expressed as the standard error of the mean) of the judged target distance grew linearly (r^2 = 96.5%) with increasing referent distance, and Figure 3(b) shows that absolute error also grew linearly (r^2 = 93.7%) with increasing referent distance; Figure 3(b) also shows a main effect

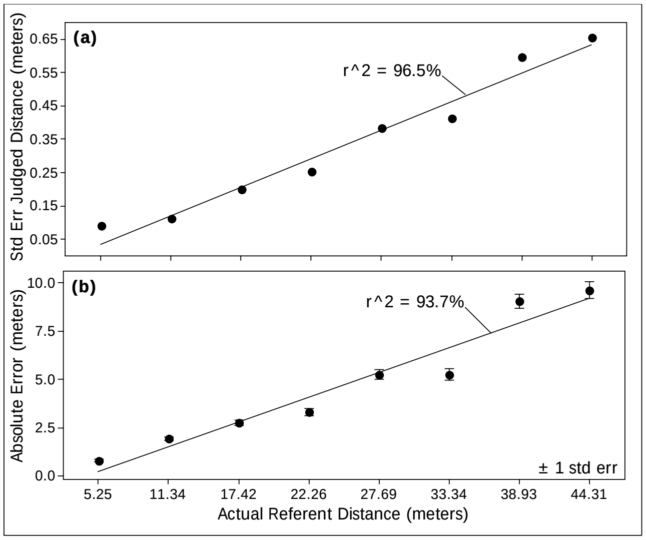


Figure 3: As the referent distance increased, (a) the variability and (b) the absolute error of the estimated target distance grew in a linear fashion. Both regressions indicate decreasing depth cue effectiveness with distance.

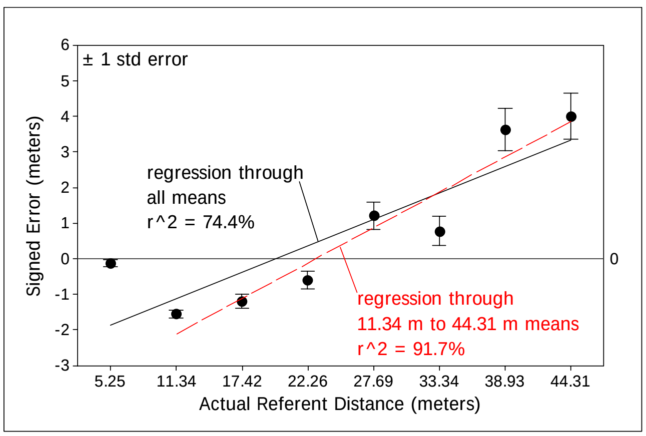


Figure 4: The effect of distance on signed error. Signed error exhibits a strong linear regression beginning at 11.34 meters, which reveals a switch in bias from underestimating to overestimating target distance at ~23 meters.

of distance on absolute error ($F(7,49)$ = 30.5, p < .000, η^2 = 29.4%). Both regressions demonstrate that our experimental task is not 2D solvable, and is in fact measuring a depth judgment, because the linear relationship with distance indicates judgments based on depth cues of linearly decreasing effectiveness (e.g., observer responses are following a Weber's law [20]). In this experiment, observers made depth judgments with virtual targets, and therefore the experiment lacks the "ground truth" that comes from tasks where observers manipulate a real-world target to match a virtual referent, such as Ellis and Menges [4] and McCandless et al. [13]. Therefore, the correlations in Figure 3 are an important validation of the experimental methodology. Loomis and Knapp [12] use a similar line of reasoning, which relates errors to depth cue availability, to validate open-loop action-based tasks, and McCandless et al. [13] found monotonic increases in both variation and error with increasing distance.

Figure 4 shows the effect of distance on signed error ($F(7,49)$ = 3.20, p = .007, η^2 = 7.31%). Like unsigned error (Figure 3), signed error shows a linear relationship with increasing distance (r^2 = 74.4%; solid line in Figure 4). However, the 5.25 meter referent weakens the linear relationship; it is likely close enough that near-field distance cues are still operating. The linear relationship between signed error and distance increases when analyzed for referents 2–8 (r^2 = 91.7%; dashed line in Figure 4). Even more interesting is a shift in bias from underestimating (referents 2–4) to overestimating (referents 5–8) distance; this bias shift is also seen in Figure 2. The bias shift occurs at around 23 meters, which is where the dashed line in Figure 4 crosses zero meters of signed error. Foley [5] found a similar bias shift, from underestimating to overestimating distance, when studying binocular disparity in isolation from all other depth cues. He found that the shift occurred in a variety of perceptual matching tasks, and although its magnitude changed between observers, it was reliably found. However, in Foley's tasks the point of veridical performance was typically found at closer distances of 1–4 meters. The similarity of this finding to Foley's suggests that stereo disparity is an important depth cue in this experimental setting.

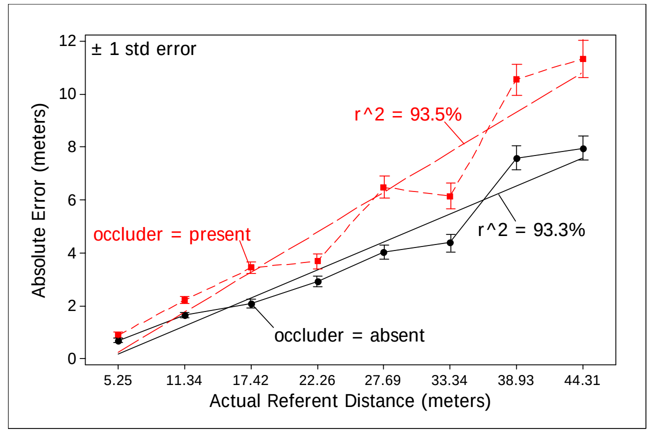


Figure 5: Effect of occluder by distance on absolute error. Observers had more error in the occluded (x-ray vision) condition (dashed line and points) than in the non-occluded condition (solid line and points), and the difference between the occluded and non-occluded conditions increased with increasing distance.

We found a main effect of occluder on absolute error ($F(1,7)$ = 5.78, p = .047, η^2 = 2.28%); when the occluder was absent, observers made an average depth judgment error of 3.91 meters, versus 5.59 meters when the occluder was present. This effect was expected because fewer depth cues are available when the occluder is present. We also found an occluder by distance interaction on absolute error (Figure 5, $F(7,49)$ = 2.06, p = .066; η^2 = .97%). When an occluder was present (the x-ray vision condition), observers had more error then when the occluder was absent, and the difference between the occluder present and occluder absent conditions increased with increasing distance. Figure 5 shows a linear modeling of the occluder present condition (dashed line), which explains r^2 = 93.5% of the observed variance, and a linear modeling of the occluder absent condition (solid line), which explains r^2 = 93.3% of the observed variance. These two linear models allow us to estimate the magnitude of the occluder effect according to distance:

$$y_{\text{present}} - y_{\text{absent}} = .08x - .33, \tag{1}$$

where y_{present} is the occluder present (dashed) line, y_{absent} is the occluder absent (solid) line, and x is distance. This equation says that for every additional meter of distance, observers made 8 cm

Proceedings of IEEE Virtual Reality 2006, March 25–29, pages 19–26, Alexandria, Virginia, USA, © 2006 IEEE
Awarded ***Honorable Mention*** *as one of 3 best papers at VR 2006*

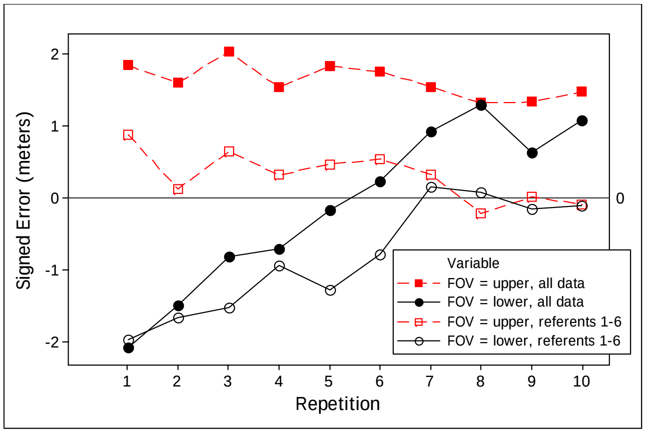


Figure 6: Effect of field of view (FOV) by repetition on signed error. Solid shapes (■,●) are means for all the data; hollow shapes (□,○) are means for the first six referents. Squares (■,□) are referents in the upper field of view; circles (●,○) are referents in the lower field of view. For clarity, standard error bars are not shown.

of additional error in the occluder present versus the occluder absent condition.

We found a field of view by repetition interaction on signed error ($F(9,63) = 3.24$, $p = .003$; $\eta^2 = .72\%$). This is shown by the solid shapes (■,●) in Figure 6. When the referents were in the upper field of view (■, mounted on the ceiling), observers overestimated their distance by about 1.5 meters, and when the referents were in the lower field of view (●, mounted on the floor), observers began with an underestimation (low repetitions), and with practice, by repetition 8 matched the overestimation of the upper field of view. The general bias towards overestimation can be explained by the overestimation of the last two referents, as seen in Figures 2 and 4. In Figure 6 the hollow shapes (□,○) show the field of view by repetition interaction when the last two referents are removed; the interaction is still significant for this reduced data set ($F(9,63) = 2.44$, $p = .019$; $\eta^2 = 1.02\%$). When the referents were in the upper field of view (□), observers did not show a bias, and by repetition 7 were quite accurate. For referents in the lower field of view (○), observers initially demonstrated the same underestimation as they did for the full data set, and with practice, by repetition 7 matched the veridical performance of the upper field of view (□) referents.

These results raise the question as to why distance judgments of referents in the lower field of view were initially underestimated. We propose that the results for repetitions 1–3 of the lower field of view referents (○) demonstrate the same distance underestimation that has been demonstrated by VR environment studies [3, 8, 12, 14, 17, 22, 25, 26]. All of these studies share the following properties: (1) they demonstrated distance underestimation for virtual environments presented in HMDs; (2) they measured distance judgments to referent objects in the lower field of view (placed on the ground plane); (3) they used open-loop action-based tasks (primarily visually directed walking and triangulation by walking); and (4) observers completed 1–3 repetitions of each experimental condition[1]. The results for repetitions 1–3 of the lower field of view referents (○) share all of these properties except for property 3: here the underestimation is demonstrated with a perceptual matching task (although Wu, Ooi, and He [26] found the underestimation for both a perceptual matching and a visually directed walking task).

Wu, Ooi, and He [26] also found that, with 2 repetitions and when observers cannot look around, a vertical view subtending 29.6° is adequate for accurate depth judgments, but a vertical view subtending 21.1° causes distance underestimation. This compares to the transparent window of our display, which allows a 21.3° vertical view. It is possible that this explains the distance underestimation for the first several repetitions of the lower field of view referents (○). But regardless of the explanation, the facts that (1) with practice observers became more accurate when placing lower field of view referents and (2) the methodologies of this study and the VR depth underestimation studies [3, 8, 12, 14, 17, 22, 25, 26] were very similar, suggest that the general VR distance underestimation effect might be transitory, and could disappear with practice.

4. Discussion

As mentioned in the Introduction, AR has many compelling applications, but many will not be realized until we understand how to place graphical objects in depth relative to real-world objects. This is difficult because imperfect AR displays and novel AR perceptual situations such as x-ray vision result in conflicting depth cues. Egocentric distance perception in the real world is not yet completely understood (Loomis and Knapp [12]), and its operation in VR is currently an active research area. Even less is known about how egocentric distance perception operates in AR settings; the comprehensive survey in Section 2 found only five previously published papers describing unique experiments. The current study contributes to the important task of understanding AR depth perception.

To our knowledge, we have conducted the first experiment that has measured AR depth judgments at medium- and far-field distances, which are important distances for a number of compelling AR applications. We have demonstrated a perceptual matching task, and found a linear relationship between distance and depth judgment variability and error (Figure 3), which argues for the validity of our results. We have also detected evidence for a switch in bias, from underestimating to overestimating distance, at ~23 meters (Figure 4), and we have made an initial quantification of how much more difficult the depth judgment task is in the x-ray vision condition (Figure 5). Finally, we found an effect of field of view in the form of an interaction with repetition (Figure 6). We suggest that part of this interaction replicates the VR depth underestimation problem, and further suggest that the effect of practice on VR depth underestimation should be explored.

The finding of a bias switch at ~23 meters (Figure 4) immediately suggests distorting the graphics so that depth is judged veridically regardless of distance. However, before pursuing this goal, the reliability of the bias switch needs to be verified by additional studies, especially ones which utilize open-loop action-based depth judgment tasks such as visually directed walking or triangulation by walking. In addition to verifying the bias switch, such studies would allow us to more closely compare our results to the VR depth perception literature. If the bias switch proves to be reliable, an important theoretical goal would be to explain, in the language of cue theory, precisely why it occurs. Such a description would likely indicate the most efficient way to counteract the bias switch.

[1] Messing and Durgin [14] point out that the small number of repetitions is part of the visually directed walking methodology; this is done so that observers do not develop strategies (such as counting footsteps) which do not depend on egocentric distance perception.

5. Methodological Improvements

In hindsight, we have determined at least two areas where the reported experimental methodology needs improvement:

- In our study observers' eyes were all at the same height, but there is ample evidence that the human visual system uses the angular declination below the horizon as an absolute egocentric distance cue for objects on the ground plane [12, 16]. Because this is calibrated by an individual's eye height, future studies should place observers at their standing eye height.
- Our targets used a high-contrast white border around a featureless interior (Figure 1). This high-contrast border is a very salient cue for stereo disparity judgments; and it is known that stereo disparity is more sensitive in the center of the visual field [7]. In our study design the target became smaller as the distance increased, and this could have made stereo disparity a more salient cue with increasing distance. Future studies should consider and perhaps control for this potentially confounding depth cue.

Acknowledgements

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Summary Statement

Summary of Service Activities

I have enjoyed giving back to the organizations that make my scientific career possible, including my employer, the agencies which have funded my work, the professional societies that organize the conferences and workshops that I attend, and my colleagues performing related work around the world. In particular, I enjoy working with others to make practical things happen, such as organizing conferences, determining which papers to accept, or which new faculty candidates to hire.

University Service: Since arriving at MSU, my goal has been to be a good citizen of the Computer Science and Engineering Department, the College of Engineering, and Mississippi State University. I seek to attain this goal by constructively contributing service activities to each of these entities. To date my university service activities have primarily been focused on the needs of the Computer Science and Engineering department, where I have served on the faculty search committee and numerous other departmental committees. In terms of university-wide service, since 2007 I have served on the Steering Committee of the Institute for Neurocognitive Science and Technology, in the past year I chaired a Five Year Program Review committee for the Department of Psychology, and this year I am beginning a 3-year term as an alternate member of MSU's Human Subjects Institutional Review Board. In addition, every semester since 2005 I have contributed questions for the Computer Science PhD Qualifying exam, and every semester since 2006 I have also contributed questions for the Computer Engineering PhD Qualifying exam.

Professional Tutorials: In the early 2000's it became apparent to many in my fields of augmented reality, virtual reality, and visualization that human-subject experiments were needed both to understand the way humans perceive, manipulate, and cognate with computer-generated graphical information, and to quantify the utility of graphical information in different application contexts. However, these fields have mostly been populated by computer scientists and engineers, who typically do not have strong backgrounds in empirical techniques. I learned empirical methods during my master's degree studies in human-computer interaction. These circumstances lead to my organizing a professional tutorial specifically aimed at teaching empirical techniques for conducting human-subjects experiments; I have collaboratively taught this tutorial with colleagues from NASA Ames Research Laboratory, The Naval Research Laboratory, and Virginia Tech. Since I have been at MSU, I have offered the tutorial 7 times, at both the *IEEE Virtual Reality* and *IEEE Visualization* conferences. This tutorial has been well-received; twice it had the highest attendance of any tutorial at the conference, and several times I have been specifically asked to offer it again the following year. In addition, the collaboration with NASA scientists lead to a moderate amount of NASA research funding, the opportunity to spend Summer 2006 pursuing a Faculty Summer Fellowship at NASA Ames Research Laboratory, and a successful single-PI 3-year NSF award that involves a collaboration with my NASA colleagues. I plan to continue to offer variations of this tutorial in several professional contexts.

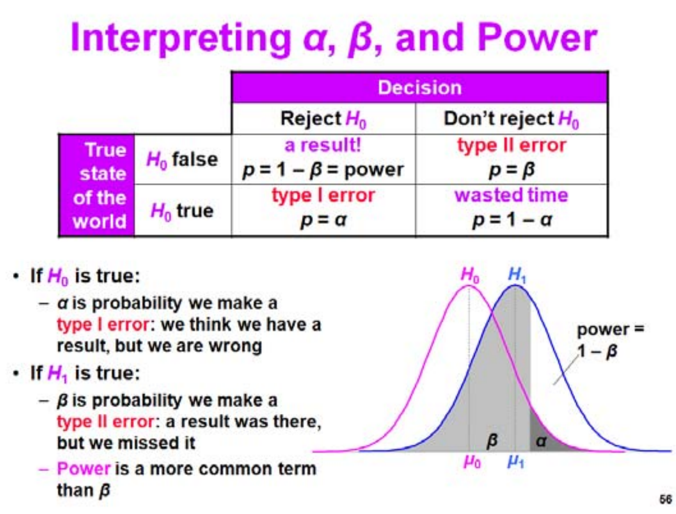
Professional Service: I have long enjoyed giving back to my professional community; indeed, I have been holding professional conference committee positions since my graduate student days. Since arriving at MSU, I have served on 3–4 program committees every year. These have included senior reviewer positions for *IEEE Virtual Reality* 2005 and 2006, and the *International Symposium on Mixed and Augmented Reality* (ISMAR) 2009; these positions required traveling to the program committee meeting where paper accept / reject decisions were made. I have also served on 7 *National Science Foundation* (NSF) review panels, and a *Naval Research Laboratory* (NRL) review panel. In addition, I have served (and am currently serving) on the 2006, 2010, and 2011 *IEEE Virtual Reality* conference committees. Finally, when I worked for the Naval Research Laboratory, I served for many years on the *IEEE Visualization* conference committee; this service culminated in a two-year stint as Program Co-Chair in 2001 and 2002.

Musical Service: I have been studying and playing music since I was in elementary school. My primary instruments are bass, guitar, and voice. Since arriving at MSU, I have had a series of wonderful opportunities to collaborate with colleagues from the Department of Music on faculty recitals and other University musical events. Among these were participating in *MSU Summer Scholars On Stage 2008*, *2009*, and *2010* (MSU Division of Academic Outreach and Continuing Education), collaborating with Robert Damm (Department of Music) and the African Student Association on *African Night 2008* and *2009*, collaborating with Robert Damm and the Hispanic Student Association on *Latin American Night 2009*, organizing a blues band for *Staff Appreciation Day 2008*, and working with my CSE colleague Ioana Banicescu to organize a jazz band for the Fall 2009 *Center for Autonomic Computing Bi-Annual Meeting Dinner*. I have also played in a number of community contexts, including *The Cotton District Arts Festival* in 2007 and 2009, the *Johnny Cash Festival* in 2007, and the *Columbus Jazz and Blues Festival* in 2007, as well as private weddings, parties, club dates, Air Force functions in Columbus, and at Trinity Presbyterian Church. It is very enjoyable to occasionally engage in an activity that is so completely different from my typical duties, and I believe that performing music clears my mind and fosters a creative spirit that may even help me generate better research ideas.

J. Edward Swan II: Service Activities

Professional Tutorials

This section contains the title slide from the tutorials that I have organized, lead, and taught 7 times at the *IEEE Virtual Reality* and *IEEE Visualization* conferences.



A representative slide from my professional tutorial on conducting human-subject experiments.

Conducting Human-Subject Experiments with Virtual and Augmented Reality

VR 2009 Tutorial

J. Edward Swan II, Mississippi State University (organizer)
Bernard D. Adelstein, NASA Ames Research Center
Joseph L. Gabbard, Virginia Tech

VisWeek 08
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Experimental Design and Analysis for Human-Subject Visualization Experiments

IEEE Visualization 2008 Tutorial

J. Edward Swan II, Ph.D.

Department of Computer Science and Engineering
Department of Psychology (Adjunct)

Mississippi State University

Experimental Design and Analysis for Human-Subject Visualization Experiments

IEEE Visualization 2007 Tutorial

J. Edward Swan II, Ph.D.

Department of Computer Science and Engineering
Department of Psychology (Adjunct)
Institute for Neurocognitive Science and Technology

Mississippi State University

IEEE Virtual Reality
Charlotte NC March 10-14, 2007

Conducting Human-Subject Experiments with Virtual and Augmented Reality

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IEEE Visualization 2006 Tutorial

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Department of Computer Science and Engineering
Institute for Neurocognitive Science and Technology

Mississippi State University

Conducting Human-Subject Experiments with Virtual and Augmented Reality

VR 2006 Tutorial

***J. Edward Swan II**, Mississippi State University (organizer)*
***Stephen R. Ellis**, NASA Ames Research Center*
***Bernard D. Adelstein**, NASA Ames Research Center*

IEEE VR 2006
HAPTICS 2006 • 3DUI 2006
March 25-29 Alexandria, Virginia

Human-Centered Fidelity Metrics for Virtual Environment Simulations

Three Numbers from Standard Experimental Design and Analysis:
α, power, effect magnitude

VR 2005 Tutorial

J. Edward Swan II, Mississippi State University