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TITLE OF PROPOSED PROJECT **CHS: Small: How Much Virtual Reality is Enough?**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ 499,890	36 months	06/01/16	

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GM
☐ COLLABORATIVE STATUS

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CERTIFICATION PAGE

Certification for Authorized Organizational Representative (or Equivalent) or Individual Applicant

By electronically signing and submitting this proposal, the Authorized Organizational Representative (AOR) or Individual Applicant is: (1) certifying that statements made herein are true and complete to the best of his/her knowledge; and (2) agreeing to accept the obligation to comply with NSF award terms and conditions if an award is made as a result of this application. Further, the applicant is hereby providing certifications regarding conflict of interest (when applicable), drug-free workplace, debarment and suspension, lobbying activities (see below), nondiscrimination, flood hazard insurance (when applicable), responsible conduct of research, organizational support, Federal tax obligations, unpaid Federal tax liability, and criminal convictions as set forth in the NSF Proposal & Award Policies & Procedures Guide,Part I: the Grant Proposal Guide (GPG). Willful provision of false information in this application and its supporting documents or in reports required under an ensuing award is a criminal offense (U.S. Code, Title 18, Section 1001).

Certification Regarding Conflict of Interest

The AOR is required to complete certifications stating that the organization has implemented and is enforcing a written policy on conflicts of interest (COI), consistent with the provisions of AAG Chapter IV.A.; that, to the best of his/her knowledge, all financial disclosures required by the conflict of interest policy were made; and that conflicts of interest, if any, were, or prior to the organization's expenditure of any funds under the award, will be, satisfactorily managed, reduced or eliminated in accordance with the organization's conflict of interest policy. Conflicts that cannot be satisfactorily managed, reduced or eliminated and research that proceeds without the imposition of conditions or restrictions when a conflict of interest exists, must be disclosed to NSF via use of the Notifications and Requests Module in FastLane.

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Is the organization or its principals presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded from covered transactions by any Federal department or agency? Yes ☐ No ☒

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This certification is required for an award of a Federal contract, grant, or cooperative agreement exceeding $100,000 and for an award of a Federal loan or a commitment providing for the United States to insure or guarantee a loan exceeding $150,000.

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The undersigned certifies, to the best of his or her knowledge and belief, that:
(1) No Federal appropriated funds have been paid or will be paid, by or on behalf of the undersigned, to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with the awarding of any Federal contract, the making of any Federal grant, the making of any Federal loan, the entering into of any cooperative agreement, and the extension, continuation, renewal, amendment, or modification of any Federal contract, grant, loan, or cooperative agreement.
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Two sections of the National Flood Insurance Act of 1968 (42 USC §4012a and §4106) bar Federal agencies from giving financial assistance for acquisition or construction purposes in any area identified by the Federal Emergency Management Agency (FEMA) as having special flood hazards unless the:
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CERTIFICATION PAGE - CONTINUED

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(1) has filed all Federal tax returns required during the three years preceding this certification;
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AUTHORIZED ORGANIZATIONAL REPRESENTATIVE	SIGNATURE	DATE
NAME Michael A Kostyshak	Electronic Signature	Nov 16 2015 3:14PM

TELEPHONE NUMBER	EMAIL ADDRESS	FAX NUMBER
401-863-9328	michael_kostyshak@brown.edu	

Project Summary

CHS: Small: How Much Virtual Reality is Enough?

Overview We propose to quantify and describe the benefits of various levels of visual fidelity for virtual reality (VR) scientific analysis applications. By leveraging a newly completed VR display room with unparalleled fidelity, we will experimentally determine the effects of the native high fidelity in comparison to reduced fidelity that the system can simulate. We plan to study the effects of resolution, horizontal and vertical field of view, display bezels, screen corners, screen seams, and display contrast. Beyond direct modification of those display properties, we will also mimic other VR systems, both room sized and head mounted, to better understand the tradeoffs of different combinations of display fidelity. These quantitative experimental outcomes will be supplemented by more subjective feedback from scientists using the display to study planetary geology, animal kinematics, mathematics, and other areas that may develop during the course of the project. We will also supplement the results with input from visual design students "sketching" novel scientific visualization concepts, thereby helping to explore design possibilities that may not have been possible with earlier displays.
Keywords: virtual reality; display fidelity; scientific visualization; human-computer interaction; visualization evaluation

Intellectual Merit The intellectual merit of this project is fourfold. First, we will quantify how various individual elements of display fidelity correlate with visual analysis task performance in virtual reality. Because the display we will use operates at the limits of human perception, the results should generalize to almost any future display system. This will include investigating whether certain application tasks or interactions are more sensitive or robust to specific visual distractions. It will cover not only visual data analysis, but also natural interactions in virtual environments and the creative design processes. Second, we will quantify similarly the tradeoffs between some of the commonly available VR systems, e.g., cave's and head-mounted displays. The ability to mimic these particular points in the VR display design space will mean we can gather within-subjects results in one geographic location during a single session, avoiding potentially confounding variables. These first two sets of measurements will help designers of future displays make appropriate cost-benefit decisions for their applications. Third, we will expand the understanding of the VR software design space. While a VR display can be treated like a very large monitor, there are likely to be novel interaction and visualization metaphors and designs that can better leverage the higher resolution, immersion, and interactivity available. In addition to exploring the software design space via new applications, we expect that scientist users will also provide feedback on the value of various levels of visual fidelity. Fourth, we will disseminate our software for display mimicry so that others can execute similar studies. The software will underlie our VR software development system so that many of our scientific applications can have visual fidelity reduced in a controlled manner with low development overhead.

Broader Impact. The broader impact of this work is to any potential applications of virtual reality, from science to entertainment to defense. All have the potential to build better display devices, software, and content informed by the knowledge that we propose to gather. The software we produce has the potential to enable others to replicate, refine, and extend the knowledge to other application areas and to other display contexts. We are particularly hopeful that the knowledge we gather will accelerate sciences that study complex, three-dimensional data and systems, since scientific applications are our particular passion and since those types of applications seem particularly ripe for virtual reality solutions.

TABLE OF CONTENTS

For font size and page formatting specifications, see PAPPG section II.B.2.

Appendix Items:

*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.

Project Description

CHS: Small: How Much Virtual Reality is Enough?

We propose a research plan to advance understanding of the value of virtual reality (VR) for science, in particular focusing on understanding the effect of several aspects of fidelity or quality of a virtual-reality display. The work is motivated by decades of research and experience using VR at Brown and by the availability of a recently completed VR display room at Brown with fidelity approaching human perceptual limits. The work is timely, given a renewed emphasis on VR in in the last few years in the technology and entertainment sectors.

We propose four specific aims.

First, we will experimentally measure user performance as we vary individual elements of VR display fidelity. We will vary resolution, brightness, and contrast from their highest levels down to levels commonly in use today. Similarly, we will vary the horizontal and vertical display size. Finally, we will mimic other common distractors in VR displays, such as CRT bezels, projection-surface corners, and image seams. For each such experiment, the other elements of fidelity will remain at their native high levels for our display. These levels are at or close to human perceptual limits.

Second, we will quantify similarly the tradeoffs between some of the commonly available VR systems, e.g., cave's and head-mounted displays. The ability to mimic these particular points in the VR display design space will mean we can gather within-subjects results in one geographic location during a single session, avoiding potentially confounding variables.

Third, we will expand the understanding of the VR software design space through observation of and interviews with scientists using software in their research and teaching. While a VR display can be treated like a very large monitor, there are likely to be novel interaction and visualization metaphors and designs that can better leverage the higher resolution, immersion, and interactivity available. In addition to exploring the software design space via new applications, we expect that scientist users will also provide feedback on the value of various levels of visual fidelity.

Fourth, we will disseminate our software for display mimicry so that others can execute similar studies. The software will underlie our VR software development system so that many of our scientific applications can have visual fidelity reduced in a controlled manner with low development overhead.

There are several scientific areas represented in the user base of our VR systems at Brown, including planetary geology, mathematics, systems biology, chemistry, and digital humanities. The Center for Computation and Visualization (CCV) at Brown is also reaching out to new potential users of our nascent new display, so we expect this user base to grow significantly. These users will be the source of our observational work, not only in the context of display fidelity but also in the context of understanding interaction and visualization approaches that better leverage VR for science.

a Research Contributions and Intellectual Merit

The contributions of this work will include experimental results quantifying the value of a number of elements of virtual reality display fidelity. The experiments will be done in the context of scientific users analyzing or exploring complex scientific data. They will include objective measures of performance, subjective analysis of behavior, anecdotal observations of behavior and performance, and interviews. These results will form the basis for a set of design guidelines for future VR displays as well as serving as inspiration for novel VR approaches worthy of further pursuit. We will also create and disseminate software making analogous experiments easier to run at other sites.

a.1 Experimental Quantification of Benefits of VR Fidelity

One main contributions of this proposal will be experimental measurements quantifying the benefits of both individual elements of VR fidelity and combinations that match other display systems. These results will be able to provide a better understanding of how VR can best leverage human visual processing capabilities. Until now, these capabilities have been mostly limited by display hardware. With our display, the properties of the display mostly reach the limits of human perception. Thus the results should have significant longevity and should help to guide future designers of VR display systems.

a.2 Feedback from Anecdotal VR Usage for Science

While less quantitative, we also expect contributions to include input and feedback from use of the display by scientists studying their own scientific data and phenomena. Much of the motivation and background for this work has come from such interactions, some of which we have reported in the past [van Dam et al., 2000, 2002].

a.3 Novel VR Approaches

The users we will work with will start with existing VR software, but we expect that they will discover creative novel VR modes of use that we will be able to report on as we observe and record their VR work. These discoveries are common with enabling technology such as we will be using. Initially, the enabling technology provides an expected boost in performance, but, as it is used, novel and unexpected applications can emerge.

a.4 Design Guidelines for Future VR Displays

The quantitative and qualitative input we will gather will distill into design guidelines that can help in evaluating the benefits and costs of various levels of display fidelity in future VR displays.

a.5 Software for VR Display Mimicry

We will develop and make available software for mimicking one VR display environment within another by artificially reducing elements of VR fidelity. This layer of software will be the basis for many of our experiments, and so will enable others to perform analogous experiments that will complement or reproduce ours. The software will also help make VR applications that build upon it more portable among different VR display systems.

b Broader Impact of the Proposed Work

The broader impact of the proposed work is a combination of broader applicability of the experimental results, training of knowledge workers to strengthen the sector, and some exposure of the lay public to science and scientific uses of VR.

The results should guide not only future VR hardware designers in creating new displays, but also VR software designers in leveraging the strengths of the displays becoming available that match human perceptual capabilities. While such a display costs millions of dollars today, in perhaps 15-20 years, it is reasonably likely to cost the equivalent of a few hundred dollars. Given a technology adoption time of about the same length, now is the right time to understand the future pinnacle of this emerging technology.

While our evaluations will be aimed at scientific inquiry, much of our software tool design process is informed by traditional visual and interaction design processes, as might be taught at our neighboring school,

Figure 1: A recent visit by middle school girls to Brown's new VR display room, the Yurt. The room provides 360 degree surround as well as a fully projected floor and partial ceiling, completely filling a typical user's field of view. Resolution and brightness are outstanding. The display is a big draw, and school groups regularly request to visit.

the Rhode Island School of Design. Some of our preliminary work illustrates that connection. Because of this focus on design, we expect that many of our results will generalize to many other domains, including education, training, medical treatment, entertainment, product design, and product review.

We will train a small number of students directly through the work proposed but will also expose a larger group of students to the research through courses. Courses that the PI teaches that will be directly connected to the research (see Curriculum Development Activities, Sec. b.1) will amplify this small number to several dozen. These students will get direct experience with interdisciplinary computational research, expanding our workforce in this valuable dimension.

The display system we will use, the YURT, is an excellent mechanism for attracting members of the public of all ages and engaging them in the scientific work that we are doing. In the last six months, since the opening of the display, several hundred visitors have visited and seen the scientific potential. Visitors have included many students, both K-12 and college level, teachers, local technology advocates, and press. One recent visit is shown in Fig. 1. The Boston Globe wrote and illustrated an excellent summary of the display and its potential [Katz], and other press have also covered its debut [Flanagan; Xu].

b.1 Curriculum Development Activities

Beyond the direct training of students performing the proposed research, we will gather information about display functionality in several courses. One, "Interdisciplinary Scientific Visualization" centers around designing and executing research projects by emulating the US model of research design, funding, and execution. Students identify a research problem with a collaborator from another discipline, explore potential solutions, write a "funding" proposal, peer review the set of proposals, do the research, write it up, and present it. This is all done during one 13 week semester. They get a taste of the excitement, challenge, and risk inherent to interdisciplinary research in a context where the real risk is minimal. This class will serve as a first line of outreach for our proposed work, broadening exposure from the handful of students directly involved as research assistants to a dozen or more each time it is taught. We will target small evaluations related to the proposed work as course projects. From past experience, we expect that some of these students will go on to participate actively in the proposed work or other research projects. A number of past students in this class are now in successful research careers.

A second course, "Virtual Reality Design for Science" has already influenced the proposed work. This course, jointly listed and taught at Brown and the Rhode Island School of Design, teaches design students enough science so that they can author mockups of new interactive tools for scientists [Keefe and Laidlaw, 2013; Keefe et al., 2005]. Scientists evaluate their tools, and some tools go on to implementation and scientific use. This influence also works the other direction, by harnessing a group of creative, artistic minds to invent new visual representations and interaction approaches that can leverage the new technology. Students in the currently running class have created responses to our prompts that, sometimes accidentally, benefit from the high resolution, high contrast, vibrant colors, and large space the new display provides.

Two other courses show students particular disciplinary data: planet surface data [Forsberg et al., 2006a], and scans of a 250' by 4' tapestry otherwise impossible to view all at once [gar]. A third offers digital humanities students an opportunity to create and show interactive digital poetry in VR. These courses, their instructors, and their students all have the potential to inform our work but also represent the broader impact of the work we are proposing. They exemplify the valuable synergy between research and teaching.

c Significance

This section describes past research related to our proposed work to put it in context and to support its potential significance.

c.1 Significance of Evaluating VR Fidelity

While there has been some work to evaluate the effects of VR fidelity, there remain substantial gaps in our understanding of the value of truly immersive displays, of the impact of different element of fidelity on that value, and of the negative effects of limitations within such displays.

The proposed experiments will analyze the benefits of display fidelity in VR systems at an unprecedented level of detail. Display fidelity is defined as the objective degree to which the sensory stimuli produced by a system correspond to real- world sensory stimuli (Ragan et al. [2013], McMahan et al. [2012]). It directly influences the level of immersion achievable by a VR environment and in turn that systems ability to promote the feeling of presence in users (Slater [2003]). However, not every display characteristic has the same amount of impact on the delivered immersion. Studies by Prabhat et al. [2008], Ragan et al. [2013] and Laha et al. [2014] have analyzed some effects of stereoscopy, head tracking, field of regard and display size on user immersion and performance in various exploration data tasks. We will use our newly completed VR system to verify previous results and evaluate aspects of fidelity that are currently unexplored due to the limits in past display hardware.

Studies by [Ware and Franck, 1996] quantified some benefits of stereo and head tracking in tasks involving 3D graph analysis. They also established that acuity above the commonly accepted perceptual limit helps with stereo perception [Ware and Mitchell, 2005]. We should be able to measure whether these effects are measurable in a less controlled large display.

Operating at the edge of human perception allows us to assess the influence of VR fidelity in a way that is likely to generalize to future displays and users, since displays with, for example, higher resolution will typically not be perceptually different.

c.2 Significance of Mimicking VR Configurations and Evaluating Them

There have been a number of past studies comparing different VR environments, e.g., a fishtank VR system and a cave [Demiralp et al., 2003; Schulze and Forsberg, 2005; Qi et al., 2006; Prabhat et al., 2008]. These studies have produced moderately inconsistent results, probably because of differences between multiple uncontrollable factors in the experimental conditions. We believe that our proposed approach will help to establish the underlying fidelity factors affecting results like these, because the different VR form factors can all be emulated within our display system, helping to avoid many kind of confounding nuisance variables. Even in the most rigorous experimental setup a change of the VR system will cause hardware-dependent variance in the fidelity characteristics of the display. Since these external variables can confound experiment outcomes, we propose to build a software environment that allows the simulation of various existing VR setups in our own system. Apart from high resolution and contrast, our system is designed to minimize visual artifacts caused by individual screen boundaries. This gives us the capability to simulate a wide range of display fidelity combinations found in existing VR setups. Running experiments between simulated environments will avoid differences in otherwise hard to control experimental variables, such as color contrast and tracking system ac

The space of possible VR displays configurations is too large to comprehensively study, with many variations of the individual elements of fidelity as well as of the specific form factors Cruz-Neira et al. [1993]; DeFanti et al. [2009]; Febretti et al. [2013]; Marks et al. [2014]; Papadopoulos et al. [2015]; Stuerzlinger et al. [2015]. Each of these displays represents a different combination of levels of fidelity. It would be virtually impossible to comprehensively explore all combinations. Our experiments varying one or two elements of fidelity will help understand this space to some extent, especially near the perceptual boundaries, but it may not generalize to arbitrary combinations.

Work at Virginia Tech provides evidence that simulation of one display form factor can be used to evaluate that form factor within another, more capable one Bowman et al. [2012] Laha et al. [2013]. The performed experiments showed consistent user performance between real and simulated VR systems when evaluating the field-of-regard and head-tracking fidelity components. However, both studies acknowledge that host systems with higher display fidelity are needed for more advanced simulations.

Emulating several such combinations of fidelity will be significant in two primary ways. First, it will provide some evidence about whether the single-factor experimental results will generalize. Second, it will help to compare common form factors with better control over elements of fidelity and without some possibly confounding differences such as geography or setting.

With the recent rise of head-mounted VR hardware (Roberts et al. [2014]) and the introduction of new large-scale VR rooms (e.g. Papadopoulos et al. [2015]) cross-system evaluation is highly significant for future development.

We will base our system for VR display mimicking on the open-source VRG3D framework [vrg] developed at Brown University.

c.3 Significance of Anecdotal VR User Feedback

While quantitative experimental results have great value and appeal, they are time consuming to gather and the they are intrinsically limited in scope. The anecdotal feedback we will gather, both before and during our quantitative experiments, will provide new observations about the value of various aspects of VR, including fidelity but also likely including interaction metaphors, visualization approaches, and things we have not yet considered. Given the early state of research in this area, gathering and reporting such observations is an appropriate element of the research [Kosara et al., 2003; Isenberg et al., 2013; Tor].

There are numerous examples of visualization and VR research results where unstructured observations or anecdotes are a valuable component of the research results [Tory and Staub-French, 2008; Plaisant et al., 2008].

d Preliminary Results

This section describes results, infrastructure, and collaborations already executed or in place that help support that the proposed work will be successful.

d.1 Yurt VR Display

Our work leverages a new VR display called the Yurt, with resolution matching human acuity. It is a roughly oval room 12'x16' in size with 8' tall walls. The walls are entirely rear projected, with the main front wall covering one half of the total. It is illuminated with 28 projectors, each with 2M pixels (1920x1080). On that display screen, the size of each pixel, from an 8' viewing distance, is approximately 1 arc-minute, which is equivalent to the acuity of the human eye [Yanoff and Duker, 2009].

The Yurt provides 360 degree surround horizontally. Two large doors close to provide a back wall with three narrow seams where imagery does not overlap. Otherwise, the surrounding imagery is seamlessly blended. The floor is also rear projected, meeting the horizontal walls without a gap. Similarly, there is a partial conical ceiling. A user's visual field is completely filled facing the front wall, even with substantial eye, head, and body motion. The display is described briefly in [Kenyon et al., 2014].

The display is central to our efforts, and its availability enables the approach we describe, which relies on a display matching human perception as closely as possible and with the ability to mimic other displays.

d.2 Display Mimicry Prototype

In Spring 2014, as part of a class project, a student developed prototype software that mimicked a 4-wall cave within the Yurt. At that time, the Yurt was not complete enough for an user study to be run. Nonetheless, the exercise provides a starting point for further refining the software developed and a proof of concept that the software development approach is tenable. The project used the VRG3D-based approach we plan to follow, and was able to mimic one environment within the other.

d.3 Experience with VR for Science Course

Laidlaw is currently co-teaching the 5th iteration of "Virtual Reality Design for Science," where design students author mock-ups of VR applications for scientists. RISD professor Fritz Drury is his co-instructor and biology professors Steve Gatesy and Joseph Crisco are all essential to the multidisciplinary effort. The process of designing and realizing mock VR application helps develop our visibility, attracting more scientists, software developers, scientific researchers, and designers. It also provides critical insights into what is working and not working with VR. The designer students in the class are part of what are essentially what Cox referred to as Renaissance Teams, blending visual designers, software developers, and scientists to collaboratively explore potential interaction and visualization approaches that leverage new technologies and and[Cox, 1988]. The knowledge and culture of our research group, which is intimately involved with the course, will help inform the design of experiments and the further development of meaningful scientific

d.4 Collaborative VR Evaluation

As part of an NSF-funded collaboration with VR researchers at Virginia Tech we are verifying a previous experiment regarding the effect of stereoscopy, head-tracking and field of regard on immersion in different VR displays [Laha et al., 2014]. This work has informed the form of the work we propose and provides us with background that is helping us to design what we expect will be a more powerful and effective set of experiments. The current collaborative user study with 40 participants is being performed using the two VR

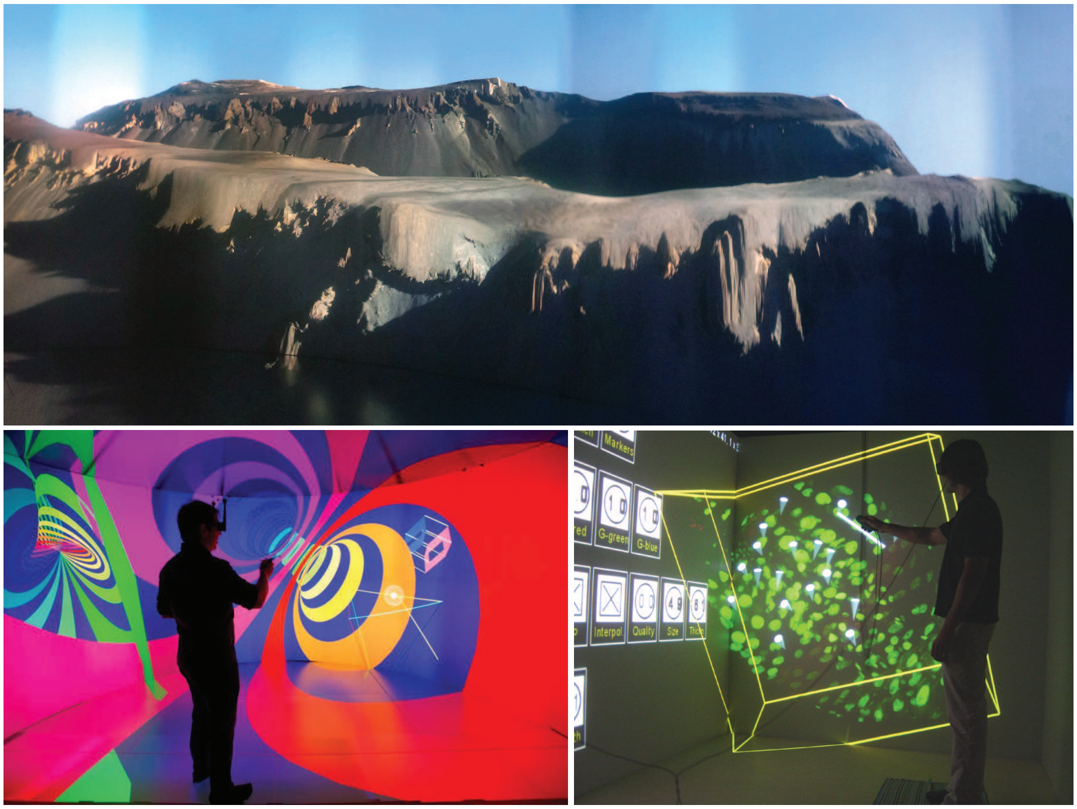

Figure 2: Examples of current collaboration projects in our VR environments. Virtual planetary exploration with Adviser on the top, an tool to examine rotations of 4-dimensional objects on the left, and biological volume exploration with CaveVox on the right.

Displays at Brown. The results of this study will provide insight into the effects of hardware-specific fidelity components on user performance in volume data exploration tasks.

d.5 VR User Base

We at Brown have decades of experience with using VR for scientific and educational applications and an established group of users and projects. The project will benefit from these existing YURT users including:

- James W. Head - planetary science, Adviser project (Forsberg et al. [2006b]
- Thomas F. Banchoff - mathematics/geometry, immersive hypercube visualization (Prabhat et al. [2005])
- Kristi Wharton - developmental cell biology, CaveVox biology volume data explorations (Prabhat et al. [2008])

d.6 VR Outreach

During the period from May to November 2015 the Yurt has been shown to about 400 visitors, with perhaps a dozen nascent collaborative scientific projects beginning to emerge from that outreach. We expect these emerging projects to both inform our proposed work and also to benefit from it, as we better establish the value of various elements of VR fidelity, develop and deploy new VR applications and approaches, and better understand the science of our collaborators.

Many of these visitors are not scientists, but help establish visibility that we hope will encourage yet further applications in the sciences and other areas.

e Research Plan

We will design, execute, and report on a series of both quantitative and informal experiments of scientific users in varying virtual reality environments. This section describes the different parts of the research, with the timeline at the end indicating how they will be arranged temporally.

e.1 Scientific and Educational User Interviews

Throughout the proposed work, and even now before it, we will interview and observe users to identify positive qualities, unexpected or unusual uses, distractions, and discoveries. We will record these findings and also use them to steer experiments as new knowledge is acquired.

e.2 Display Preparation

Before any fidelity experiments can be run, it will be necessary to tweak the display to ensure peak performance. We will also likely need to refine the calibration process to some extent, to ensure consistent performance. While not preventing current use, our system still exhibits some visual artifacts, mostly related to blending projector images and aligning them at seams. We will address two calibration concerns: fine tuning of projector blend regions and projection borders on the screen, and matching the color and contrast of all projectors in use. For both tasks we will work with hardware suppliers, and engineers from Scalable Display Technology as well as making our own adjustments, as necessary. We may also address the issue of "black" in overlapping regions, where it sums to create brighter areas. We have a solution using unfocused masking that mitigates the black problem substantially, but it does not work yet in conjunction with the blending process.

e.3 Single-Factor Experiments

Our first experiments will involve piloting the variation of single elements of fidelity from their maximum level down to the lowest levels commonly available. This will help us gauge how many steps are necessary for each element of fidelity, how sensitive measurements are likely to be, and whether tasks and stimuli are at an appropriate level of difficulty. We will then pilot varying some elements of fidelity pairwise, to look for interactions that may be important in our ultimate experiments and to gauge the same things as the single-factor pilot experiments gauged.

The elements of fidelity we will evaluate are

- Resolution will vary from full single arc-minute per pixel to approximately 4 arc-minutes per pixel, comparable to an 8' display or cave wall with 1000 pixels displayed on it. This level is also comparable to phone displays running in stereo mode using something like Google cardboard. Some displays, including Cave2 [Febretti et al., 2013], have higher resolution horizontally than vertically, and we will run pilots to determine if there is sufficient variability in results to warrant a more substantial experiment.

- Contrast will vary from about 500 to less than 100. In our past displays, contrast has been low enough that some color perception was not possible. We will likely not reach that level, since displays systems that low in contrast are not commonly available.

- Field of View and Field of Regard. We will limit these elements of fidelity both in room-related terms, as would be the case in a partial room-size display, and in head-related terms, as would be the case in a head-mounted display. The range in room-related terms will vary from the 360 of our Yurt or a 6-wall cave down to the few degrees a handheld device offers. Horizontal and vertical field of view will be varied separately, but using combinations that are commonly available. Head-related field of view will be varied to match the range commonly available in HMD's.
- Stereo We will experiment with stereo and mono display.
- Bezels or Gaps will be added virtually to our display to represent tiled arrays of monitors, which currently cannot be implemented without a gap between each pair of monitors. We hypothesize that bezels will significantly impact immersion and distraction during some common tasks, but know of no quantitative results measuring this. Bezels will be modeled on those present in other popular large-format displays.
- Corners will be emulated vertically in our round display to match their appearance in a display like a cuboidal cave. We may be able to emulate horizontal corners, like those where wall meets floor, but because we have actual corners there, we may only be able to do so in a restricted field of view condition where only the front wall is used.
- Seams occur where imagery is not blended, but abuts. We will vary several aspects of accuracy across seams, including alignment parallel to the seam, alignment perpendicular to the seam, view orientation changes across the seam, and color and brightness changes across the seam.

We will use tasks and stimuli derived from Laha's approach, which utilizes a number of typical visual scientific analysis tasks. Performance on those tasks is coded and summarized as well as captured individually for more detailed analysis. Our design will be within subjects, in order to avoid individual variation, and so we will reduce the total number of tasks to keep the experiment time within approximately one hour. The reduction in tasks will be informed by a set of in-process experiments.

e.4 Stimulus Software Development

Our current experiments use VRUI to graphically display geometry, but its use has been difficult to tailor to our display and will be even more difficult to modify for our experiments. We expect to create new display software built atop our VR library, VRG3D. The VRG3D library manages the 69 display surfaces, setting rendering parameters and warping and blending imagery across them. It will require some changes to implement the reduction in fidelity we will need. Many of those, including resolution and contrast, can be included in the warping and blending portion of rendering. Some, including bezels, corners, and field-of-view, will be implemented by changing the rendered geometry or the lighting model to include additional visual cues.

On top of our display software, we will also add logging, scripting, training, and additional sequencing elements to make the running of experiments as low-overhead as possible.

e.5 Display-Mimicking Software Development

Software for mimicking displays will be developed atop our stimulus software. Much of the mimicking will be implemented by matching the display limitations of a given alternative display one element of fidelity at a time. Some additional mimicking of areas outside the display surface itself may also need to be modeled and rendered, much as specific elements like bezels will need to be replicated. For example, for a desktop display, the desk, monitor case, and other visible context will help emulate a real display more effectively than just a void surrounding a display rectangle.

e.6 Display-Mimicking Experiments

We will use the same tasks and visual stimuli used to evaluate elements of fidelity in comparing mimicked VR displays. Current plans are to mimic Cave2, a 4-wall cave, and an HMD. However, we are hopeful that there will be time to add to this list.

e.7 Software Dissemination

Our mimicking and fidelity-reduction software will be distributed using the same mechanisms as our VRG3D library. Indeed, we expect some parts of it to be within the VRG3D software, itself. Throughout the duration of the project, versions of the system will be deployed to the public as an open-source project via SourceForge, using their public license derived from the GNU General Public License. The software will be implemented in C++ under linux.

e.8 Scientific and Educational User Interviews

Throughout the course of the proposed work, we will interact with scientific users of the Yurt to gather their feedback on what is working, what limitations they notice, whether they are able to accomplish their scientific tasks, and other topics relevant to understanding VR. As has been the case in generating plans for this research, we expect these interactions and observations to guide future research, perhaps suggesting improvements to displays, to visual representations, or to interaction approaches. We will endeavor to be responsive to the results of these collaborative discussions.

e.9 Timeline

Our plan is divided into three years, with multiple evaluatable milestones.

As mentioned, throughout the 3 years, we will also interview scientific and educational users to gather anecdotal input that we will use to refine our experimental tasks and designs, as appropriate. These interviews are not reflected in the schedule as we expect them to be serendipitous, depending on unpredictable findings.

Year 1 Milestones

- **Q1** VR display fine tuned
- **Q2** tasks, stimuli for single-variable experiments finalized
- **Q3** fidelity-limiting and stimulus presentation software complete
- **Q4** pilots of half of single-variable experiments complete

Year 2 Milestones

- **Q1** first half of single-variable experiments run
- **Q2** second half of single-variable experiments run
- **Q2** display-mimicking software layer complete
- **Q3** mimicked environments for 3 other displays complete: Cave2, HMD, and 4-wall cave
- **Q4** single-variable experiments analyzed, written up, and submitted
- **Q4** display-mimicking software and specific environments initial release

Year 3 Milestones

- **Q2** experiments for 3 mimicked environments run
- **Q4** display-mimicking results analyzed, written up, and submitted
- **Q4** software and specific environments final release
- **Q4** anecdotal results analyzed, written up, and submitted.

f Results from Prior NSF Support

f.1 OCI-0923393

Laidlaw is the PI on a recently completed NSF award OCI-0923393, “MRI: Development of a Next-Generation Interactive Virtual-Reality Display Environment for Science” $2M, 2009-2015.

Intellectual Merit

At this time, display design, development, and construction is complete, but there have been only a few oral presentations and one poster presentation about it. No papers have been produced under this award yet.

Broader Impact

Some of the broader impact will be in results from studies that the display enables, such as those proposed here. Additional impact will come from discoveries that will be made using the new display in fluid dynamics, biology, physics, archaeology, and other disciplines.

f.2 IIS-1016623

Laidlaw was also a Co-PI on a collaborative award IIS-1016623, “GV: Small: Collaborative Research: Supporting Knowledge Discovery through a Scientific Visualization Language,” $269K, 2010-2014.

Intellectual Merit

Publications include ([Gomez and Laidlaw, 2012; Gomez et al., 2012; Ziemkiewicz et al., 2012; Gomez et al., 2014] from Laidlaw’s group at Brown along with several others from their collaborative groups. All are aimed at improving the scientific analysis of diffusion MRI data.

Broader Impact

The broader impact will be in a better understanding of brains and of how they can effectively be studied as well as a better understanding of the principles underlying effective scientific visualization.

g Summary

In summary, we propose to leverage a human-perception level virtual reality display to gain and quantify insights about the value of various element of VR fidelity for scientific analysis applications. We believe that this work will advance the field in ways that will help computer scientists create better software tools, scientists use VR to accelerate their analysis needs, and the growing industry around virtual reality to make better targeted and more appropriate displays for many purposes.

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Professional Preparation

Brown University, Providence, RI	Computer Science	Sc.B., 1983
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Brown University; Providence, RI	Computer Science	Sc.M., 1985
Caltech; Pasadena, CA	Computer Science	M.S., 1992
Caltech, Pasadena, CA	Computer Science	Ph.D., 1995

Appointments

2008-present Professor, Computer Science Department, Brown University
2003-2008 Associate Professor, Computer Science Department, Brown University
2000-2003 Stephen Robert Assistant Professor, CS Department, Brown University
1998-2000 Assistant Professor, Computer Science Department, Brown University
1996-1998 Senior Research Fellow, Division of Biology, Caltech
1989-1996 Postdoctoral Research Fellow/Research Assistant, Computer Science, Caltech
1989-1993 Consultant Stardent/Advanced Visual Systems
1986-1989 Software Engineer, Stellar Computer

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Synergistic Activities

A graduate/undergraduate class, *Interdisciplinary Scientific Visualization*, explores design issues in scientific visualization from two perspectives: visual design and computer science. The course is co-taught with Rhode Island School of Design (RISD) Illustration Department Chairman Fritz Drury and biologist Sharon Swartz. Together we worked with students from both RISD and Brown to design and realize new virtual reality interfaces for exploring 3D time-varying flow. Students learn about communicating and working with researchers across multiple fields.

Co-taught one-day course at premiere computer graphics conference, SIGGRAPH, about using art-based methods for scientific visualization. I led a two-hour session where approximately 80 computer graphics professionals used traditional art media (paint, charcoal, markers, chalk, etc.) to represent multivalued scientific data.

Was a main designer and developer of AVS, a visualization software product created at Stellar Computer in the 80's. It is widely used to process and visualize scientific data from many disciplines.

Advised and continue to recruit undergraduates for research projects both at Brown and, previously, at Caltech. Many of the projects have culminated in research publications. Several have been with women in computer science, a traditionally underrepresented group. Coordinating a crew of undergraduates to work on projects in a new virtual reality cave, to be brought online in the next year.

Collaborators and Other Affiliations

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Total number of Collaborators and Co-Editors (122)

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Total number of Graduate Advisors and Postdoctoral Sponsor (2)

Thesis Advisor and Postgraduate-Scholar Sponsor**:** Daniel Acevedo-Feliz; KAUST, Stuart Andrews; Columbia, Ryan Cabeen, Jian Chen; UMD/BC, Cullen Jackson; Aptima, Steven Gomez, Connor Gramazio, Hua Guo, Daniel Keefe; UMinn, R. Michael Kirby, Georgeta Elizabeth Marai; UChicago, Paul Reitsma; CMU, Eileen Vote, Song Zhang.
Total number of Thesis and Postgraduate Scholar Advisees (14)

Current and Pending Support
(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: David Laidlaw

Where else this proposal is being submitted:

Support: ☐ Current ☑ Pending ☐ Submission Planned in Near Future ☐ Transfer of Support
Project/Proposal Title: CHS: Small: How Much Virtual Reality is Enough?
Source of Support: NSF
Total Award Amount: $499,887 Total Award Period Covered: 06/01/2016 - 05/31/2019
Location of Project: Brown University
Person-Months Per Year Committed to Project: Cal: 0.00 Acad: 0.00 Sumr: 0.70

Support: ☐ Current ☑ Pending ☐ Submission Planned in Near Future ☐ Transfer of Support
Project/Proposal Title: Gaining insight into nutrient fields and water column structure via interactive cognitive visualization
Source of Support: RI STAC
Total Award Amount: $53,667 Total Award Period Covered: 02/01/2016 - 01/31/2017
Location of Project: Brown University
Person-Months Per Year Committed to Project: Cal: 0.00 Acad: 0.00 Sumr: 0.25

Support: ☐ Current ☑ Pending ☐ Submission Planned in Near Future ☐ Transfer of Support
Project/Proposal Title: ITEST: Strategies: Data to Interactive Visualization Environment (DIVE): Rich Modular Learning Experiences for STEM-Based Education and Assessment
Source of Support: NSF
Total Award Amount: $1,200,000 Total Award Period Covered: 04/15/2016 - 04/14/2019
Location of Project: Brown University
Person-Months Per Year Committed to Project: Cal: 0.00 Acad: 0.00 Sumr: 1.00

Support: ☐ Current ☑ Pending ☐ Submission Planned in Near Future ☐ Transfer of Support
Project/Proposal Title: Science and Technology Centers: Integrative Partnerships: Virtual and Augmented Reality
Source of Support: NSF
Total Award Amount: $1,912,858 Total Award Period Covered: 06/01/16 - 05/31/21
Location of Project: Brown University
Person-Months Per Year Committed to Project: Cal: 0.00 Acad: 0.00 Sumr: 1.00

Support: ☑ Current ☐ Pending ☐ Submission Planned in Near Future ☐ Transfer of Support
Project/Proposal Title: CHS: Medium: Improvidng Visual Analysis Systems for Brain and Genomics Research Using Predictive Models of Sensemaking
Source of Support: NSF
Total Award Amount: $1,200,000 Total Award Period Covered: 06/01/2016 - 05/31/2020
Location of Project: Brown University
Person-Months Per Year Committed to Project: Cal: 0.00 Acad: 0.00 Sumr: 1.00

Support: ☑ Current ☐ Pending ☐ Submission Planned in Near Future ☐ Transfer of Support
Project/Proposal Title: CGV: Small: Collaborative Research: Immersive Vizualization and 3D Innteraction for Volume Data Analysis
Source of Support: NSF
Total Award Amount: $249,955 Total Award Period Covered: 08/01/13 - 07/31/16
Location of Project: Brown University
Person-Months Per Year Committed to Project: Cal: 0.00 Acad: 0.00 Sumr: 0.45

Support: ☑ Current ☐ Pending ☐ Submission Planned in Near Future ☐ Transfer of Support
Project/Proposal Title: Neuropathogenesis of clade C HIV in South Africa
Source of Support: NIH/Univ. of Missouri, St. Louis
Total Award Amount: $555,255 Total Award Period Covered: 04/01/09 - 03/31/16
Location of Project: Brown University
Person-Months Per Year Committed to Project: Cal: 0.08 Acad: 0.00 Sumr: 0.00

Brown University -General Resources in the Department of Computer Science

The Department of Computer Science provides leading-edge computing technology to all its faculty and students. We have over 500 desktop systems running Linux, OSX, or Windows. Most of these are custom-built machines configured and assembled by the department's technical staff. A standard desktop includes quad-core processors with up to 16GB of memory and dual 19" or single 24" flat-panel monitors. These systems are connected to the department's 1Gb/s switched Ethernet network with access to both Internet1 and Internet2 via the University's fiber-optic backbone. An 802.11n (300Mb/s) wireless network is accessible throughout the department.

The department has three electronic classrooms. The first, a banked auditorium, holds seventy-three systems running Linux. This room serves as the primary computer facility for undergraduate computer science students. The second contains twenty-five seats, each with a Microsoft Windows and Linux system. The layout of this space makes it an ideal room for sections, seminars, and interactive learning. The third contains an advanced audiovisual system that supports recording and streaming of lectures and talks. In its default configuration, it accommodates 50 people, but the back wall opens into an atrium, equipped with large screen TVs and speakers, providing overflow seating for around 200. Five research labs further enrich the environment with specialized hardware and advanced workstations from a variety of vendors.

Desktop and research systems are supported by a data center with fully redundant servers that offer a wide range of services. Central file storage is built upon IBM's General Parallel File System (GPFS). This approach provides a scalable, high performance, cost effective solution based on IBM hardware and currently hosts approximately 343TB of RAID-6 storage. A Sun Grid Engine cluster of 181 computational servers running Linux provides 1828 cores and over 4TB of combined memory. The most powerful of these are quad processor systems, each with a total of 64 cores and 256GB of memory.

Brown's Center for Computation and Visualization (CCV)

In addition to the computing resources already mentioned, CCV maintains a high-end visualization facility with large-scale immersive visualization capabilities. This includes a fully immersive Cave system, a multi-projector stereo display wall, and a full-surround, stereo, world-class virtual display with 100 million pixels driven by 69 HD projectors. Custom visualization solutions for software and hardware needs are available.

Equipment Statement

No Equipment requested

Data Management Plan

The goal of this data management plan is to make results and tools available to as many potential users and researchers as possible.

Data Types Produced. The proposed work will collect data from experiments with many users. That data will be primarily in the form of performance measurements for carefully controlled tasks. It will also include some written or dictated responses and demographic data. All data that is collected will be compliant with IRB standards.

We will also produce software for running virtual reality experiments.

Dissemination Plan. Public dissemination is an important goal of our lab, and it holds continued importance for the work detailed in this proposal.

Our primary dissemination of experimental results will be via peer-reviewed publications. We will also make available anonymized versions of the raw data collected during experiments

In addition to our plans for disseminating experimental data, we also intend to release our VR tools so that they can be built on by other researchers. Throughout the duration of the project, versions of the system will be deployed to the public as an open-source project via SourceForge, using their public license derived from the GNU General Public License. We have been using this approach for a virtual reality library, VRG3D, that we have developed with other NSF support (OCI-09-23393).

All Brown University Computer Science Department researchers have access to our clustered, centrally managed file servers. This cluster, built upon IBM's hardware and GPFS file system, provides over 100TB of available space. Daily, incremental backups are stored on the University's Tivoli Storage Manager backup and archival server, capable of storing multiple petabytes of data on tape. The Department maintains a website, www.cs.brown.edu, which is directly accessible by members of our community for authoring web content or for sharing data of any kind.

Collaborators List for David Laidlaw; Brown University; PI

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2. Eric T. Ahrens; CMU
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10. Sheila Bonde; Brown University
11. Doug Bowman; Virginia Polytechnic Institute & State University
12. Andrew Bragdon; Microsoft
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