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STORIES IN THE ROCK: A DESIGN CASE OF AN EXPLORABLE IMAGE VIEWER IN A NATURAL HISTORY MUSEUM

Marti Louw, *University of Pittsburgh*; Ahmed Ansari & Chris Bartley, *Carnegie Mellon University*;
Camellia Sanford, *Rockman et al.*

This design case explores the affordances of gigapixel image technology for science communication and learning in museum settings through the iterative development of an explorable image viewer to engage visitors in an archaeological exhibit. We reflect on the series of user studies, prototype iterations, and design decisions taken to optimize navigation, annotation and exploration in this zoomable user interface. We highlight a set of design precedents, interaction frameworks, and content structuring approaches, while detailing the development of a media rich digital annotation strategy to augment interpretation, commentary, and conversation about a petroglyph site. Through this work, we highlight the unique affordances of multiscalar image platforms to scaffold disciplinary observation and engagement with scientific content.

Marti Louw is Research Faculty at the University of Pittsburgh Center for Learning in Out-of-School Environments (UPCLOSE) and a Research Associate at the Carnegie Museum of Natural History. Her design research practice focuses on how emerging digital media and sensing technologies can be used to create learning experiences that support participation, engagement and shared meaning-making with science.

Ahmed Ansari completed his Interaction Design degree at Carnegie Mellon University in 2013 and now teaches design at SZABIST, Karachi, Pakistan. His academic interests involve exploring the philosophical foundations of design, and the applications of living systems theory to design research and practice, as well as to evangelize the use of design thinking and research methods in general pedagogy.

Chris Bartley is Principal Research Programmer in the CREATE Lab at Carnegie Mellon University's Robotics Institute. He works on projects that seek to effect positive, lasting, and meaningful change in communities around the world by coupling deep problems with understanding, innovation, and cultural transformation.

Camellia Sanford is a Senior Researcher at Rockman et al, a research and evaluation company that often provides external feedback to inform the design of projects in formal and informal environments. Her work primarily focuses on investigating learning and engagement in museums and through digital media.

INTRODUCTION

To see, look, notice, and begin to observe—how do we support this fundamental learning progression towards developing an expert eye? Observation as a practice requires both learning to see, and seeing to learn. Seeing itself is a first enabling condition. One must have access, resources, mentors, and often, specialized tools for looking closer and deeper. Attending to and reasoning about what seen is a second necessary condition. Finding patterns, systematically comparing and noting details, understanding which features are salient and connect to a history of past observations collectively tested over time—these are the learned aspects of disciplinary observation (Daston & Lunbeck, 2011; Norris,1985).

Museums are specialized sites for observation. Exhibits, demonstrations, and collections are displays designed to engage people in looking more intently and reasoning about what they see together. The project we describe next, while utilizing an emerging visualization technology, is at its core an effort to draw people into active observation in a museum context.

Creating Rich Learning Environments with Gigapixel Technology

Networked gigapixel image technology is an emerging class of explorable interactive media. High-resolution images displayed in zoomable, visual environments enable users to seamlessly move from full panoramic views to deep close-ups, often comprising billions of pixels. These multiscalar image viewers are most familiar in online mapping and geospatial browsing applications such as *Yahoo! Maps* and

Google Earth, but the information such viewers organize can extend well beyond maps to include large composite photographic images, and even computationally rendered data visualizations and time-series imagery.

The zoomable user interfaces (ZUIs) that gigapixel viewers employ offer a spatial way to dynamically display and organize large amounts of information in a single interface using scroll, pan, and deep zoom controls. Users can embed text, images, graphics, audio, and video at different spatial locations and zoom levels within an image, creating localized sites for annotation, commenting and conversation. Compared to earlier forms of interactive media, multi-resolution image platforms afford deeper navigational agency and observational control in a shared visual space.

Design Precedents

Our project team utilized a human-centered design research process to explore the potential of gigapixel image environments to support deep observation, engagement, and learning. To ground our design work, we established a shared set of design precedents to understand the configurations and affordances of existing gigapixel image viewing platforms, and for the team to collectively reference as we made design choices (Boling & Smith, 2012). These precedents were drawn from image-intensive commercial and educational web applications, as well as research findings and models from the learning sciences, human-computer interaction, and design research fields. This selection of prior work served as a front-end team building exercise, and grew to represent a shared visual vocabulary and set of exemplars by which to imagine and assess various design directions.

In selecting precedents, we looked for ways in which multi-resolution image platforms could support participatory learning experiences around visual evidence, and we focused on the distinctive attributes of these networked visual environments for science communication and social learning in museum contexts (Louw & Crowley, 2013). We synthesized this collected work to identify five promising affordances of gigapixel image technology for our project:

1. **DEEP LOOKING AND NOTICING IN A SHARED OBSERVATIONAL SPACE**
   Users can move seamlessly from macro to micro within an image, revealing unseen details, and encouraging visual exploration and observation. Efforts like the Google Art Project digitally archive and present ultra-high resolution online reproductions of artworks that can be searched, explored, saved and shared. In a bold move, the Rijksmuseum has gone a step further with the Rijksstudio, which enables users to freely download, embed, crop and creatively reuse images of masterpieces from their collection without copyright concern (Gorgles, 2013). The Smithsonian's Nancy Proctor notes that "*gigapixel scans by which artworks are rendered into digital streams are enabling intimate encounters with images at visual depths not possible even in the galleries*" (Proctor, 2011, p. 216).

2. **DEMOCRATIZING A TOOL OF SCIENCE**
   Gigapixel image technology makes the process of taking, storing, sharing, and interpreting high-resolution images—a domain once the purview of surveillance and defense industries—available to the general public. The hardware and software required to easily create high-resolution images is now commercially available, with much of the code being open source. Web services like GigaPan.com and Photosynth.net invite gigapixel image-makers from all over the world to upload their content to be viewed, annotated, geolocated, commented, and shared globally.

3. **ENCOURAGING PARTICIPATORY LEARNING**
   As a networked platform, the technology generates new possibilities for participatory learning and direct communication between and among disciplinary experts and the public, through crowdsourcing, open forums, and the sharing of observations and interpretation in citizen science efforts (Schoen & Stevenson, 2010). For example, the North Carolina State University (NCSU) Insect Museum began using gigapixel image technology to document their extensive insect collection, and has released over 2,700 panoramas of rare and fragile specimen drawers to the general public online. In a paper documenting the results from the project, the NCSU team reported that the platform afforded them a new public engagement opportunity whereby museum scientists and the public could interact and have conversational exchanges about insect biology (Bertone, Blinn, Dew, Seltmann, & Deans, 2012).

4. **OFFERING NEW VISUOSPATIAL WAYS TO CURATE COLLECTIONS AND ENVIRONMENTS**
   Multiscalar images enable content to be organized and accessed visually along an explorable spatial dimension. Thus, depth and distance cues in visual perception can be used to structure information, in addition to more traditional means of organizing exhibit content (e.g., thematic, chronological, geographic, hierarchical), to guide and encourage close looking. The Nature Valley Trail View is a prime example of an explorable visuospatial environment made possible by combining underlying image browsing technologies such as Google's Streetview and Microsoft's Zoom.it with geospatial data maps in a unified visual information space. Augmented reality applications such as these enable users to virtually explore and walk along trails at Yellowstone National Park or fly around London's skyline diving into highlighted points of interest. Along the way contextual callouts provide additional, interactive media overlays

for a more dynamic user experience (Bolter, Engberg, & MacIntyre, 2013).

5. **ENABLING CONTEXT-DEPENDENT ANNOTATIONS AND MEDIATION**
   Embedded information can be revealed depending on user interactions and locations within the three-dimensional image space, dynamically tying information to user exploration (Luan, Drucker, Kopf, Csu, & Cohen, 2008). A playful example of this type of context-dependent mediation can be found on the portfolio website of the Canadian design firm Castor, which displays clever media-rich annotations as a user zooms in to see details of various inspirational objects on display (Gaver & Bowers, 2012).

Clearly, explorable high-resolution media environments have the potential to extend how users approach and engage with interactive media. But to date, there has been little research or evaluation work assessing the merits of this type of technology platform for learning and engagement in museum contexts (Davis et al., 2013; Kidd, Ntala, & Lyons, 2011). Facilitating scientific or disciplinary forms of observation so that museumgoers begin to engage with artifacts and collections more critically, analytically, and systematically is a challenging prospect that requires specifically designed scaffolding and mediation (Eberbach & Crowley, in press). In addition, zoomable user interfaces raise considerable interaction and information design challenges; for example, the layout and motion of screen elements (e.g. active areas, aspect ratios, icon size, color contrast) that must work at arbitrary scales across a dynamic visual space (Bederson, 2011).

As natural and gesture-based user interfaces become standard, the question of how to develop intuitive interaction spaces that give users deeper agency and choice in how to move through content in ways that are personally relevant, becomes vitally important (Gammon & Burch, 2008). Furthermore, designs will need to account for on-the-fly, dynamic content restructuring as experiential navigation and interpretation become increasingly interdependent (Burdick, Drucker, Lunenfled, Presner, Schnapp 2012). Museum exhibit experiences must also account for myriad interests, needs, goals and expectations that a diverse public brings to these free-choice learning environments (Falk and Sheppard, 2006).

The following design case describes an effort to meet these design challenges in the context of a specific gigapixel image application: the exploration, observation and appreciation of ancient petroglyphs (rock art) and Neolithic culture in a natural history museum setting.

CONTEXT

Designing an Explorable Image Viewer for a Museum Environment

The University of Pittsburgh Center for Learning in Out-of-School Environments (UPCLOSE), in collaboration with Carnegie Mellon University's CREATE Lab and the Carnegie Museum of Natural History, is developing an NSF-funded set of demonstration projects to design and study the affordances of gigapixel-based image technology for science communication and learning in museum settings. The first demonstration project, described here, centered on finding ways to engage museum visitors in observation and meaning-making with ancient rock art.

The core design team included a design research faculty member specializing in digital media and learning, a graduate student in interaction design with a professional web design background, and a senior research programmer with expertise building big data visualization applications. The design research faculty member served both as a principal investigator and a creative lead overseeing the research, design and evaluation aspects of the project. The interaction design student, as an independent study for credit, led the user studies, the planning and prototyping of the information architecture, and the graphic design direction for the system. The lead web developer architected and implemented the software, customized a learning analytics module, and delivered a robust exhibit prototype for assessment and external impact evaluation, a grant requirement of the NSF's Advancing Informal Science Learning Program. From the outset, the design team worked in close collaboration with the Museum's curatorial, education and exhibit staff, and its visitors to realize the project.

Stories in the Rock

Dr. Sandra Olsen, Head of Anthropology and Director of the Center for World Cultures at the Carnegie Museum of Natural History, leads the Arabian Rock Art Heritage Project with a multinational team of scientists to investigate a set of little known petroglyph sites found in remote regions of the Saudi Arabian desert (Figure 1). Carved into large rock faces are extremely well preserved depictions of prehistoric people hunting wild animals, herding cattle, riding camels, and engaging in warfare on horseback. Some of these ancient rock art engravings date back to the Holocene Wet Phase (8,000 BCE–3,500 BCE), a time when the Arabian Peninsula supported a savannah, rather than desert-like environment. During her research expeditions, Dr. Olsen's team has been documenting these remarkable archeological finds using high-resolution GigaPan composite photography, polynomial texture mapping, and three-dimensional laser scanning. These visual data resources function not only as documentary evidence, but also as fascinating windows into remote and inaccessible cultural sites of great importance.

FIGURE 1. Petroglyph expert Dr. Sandra Olsen on site. *(photo credit: Dr. Chris Beard)*

The stunning panoramic images captured and the stories they reveal served as the inspiration for our *Stories in the Rock* project. The challenge the project team collectively faced was how to use an explorable image environment to communicate and engage museum visitors in seemingly arcane petroglyph research discoveries, the nuances of which can be particularly difficult to see and interpret without explicit scaffolding.

The *Stories in the Rock* demonstration project had three central aims. Firstly, to study applications of multiscalar image environments to communicate and engage visitors in museum research and collections. Secondly, to support disciplinary ways of looking, noticing and observing features in an ancient petroglyph site. Thirdly, to support user agency and personal sense-making through self-directed exploration and learning.

We next present a summary of our design process highlighting critical moments and decision points in the development of an explorable image viewer. The activities build towards fulfilling project goals—framing the possibilities and limits of gigapixel image interactions in a museum exhibit setting, generating frameworks and design concepts that met both usability and learning objectives, and finally developing an iterative series of working prototypes that we deployed for testing and evaluation on the museum floor.

DESIGN PROCESS

The design team used a combination of human-centered design research methods, both generative and evaluative, to discover and understand user needs and desires, and to assess existing gigapixel image viewing systems (Martin & Hanington, 2012). Furthermore, we took a research-through-design approach to integrate our front-end user study insights within social science-based frameworks and theories to define and reflect on design challenges in the face of emerging solutions (Burdick, 2003).

PHASE 1 | Exploratory Research

The initial project phase focused on exploratory design research to understand both user and stakeholder goals, needs, and expectations, as well as define user experience scenarios by observing engagement with existing gigapixel viewer-based technology. While time consuming, this approach had several advantages. Firstly, it gave both lay users and stakeholders ways to imagine and voice their needs and wishes through techniques such as think-aloud protocols, semi-structured interviews, and elicitation activities. It also allowed the design team to observe behaviors and individual nuances of interaction within the context of use (i.e. museum spaces), while at the same time correlating and confirming patterns of use both anecdotally and quantitatively to inform the design.

For all site observations and participatory exercises, we collected data on users' age, gender, who they came with, and their perceived level of comfort with the technology. This data was then synthesized and analyzed to establish key findings that would guide the design of an interactive exhibit experience, based on explorations, interactions, and mediation of high-resolution images.

Understanding Expert Needs & Goals

A central goal of this project is to facilitate two-way communication between scientists and the public. As a starting point, we needed to learn more about the subject matter, its interpretation, and the curator's communication and public engagement goals. To do so, we audio recorded and transcribed several semi-structured interviews with Dr. Olsen, and used a modified contextual inquiry method to understand her observational practices, as well as how she utilizes gigapixel image data in her research (Beyer & Holtzblatt, 1997). To support this inquiry, we printed a large format 3' x 6' panoramic photograph of the *Shuwaymis West* petroglyph site as a prompt, and provided post-it notes for Dr. Olsen to spatially mark points of interest and identify important topics. This physical exercise served as a way to quickly locate and visually record rich information in real time, while documenting an archaeologist's observational practice, and it provided clues as to how we might support users making more scientific kinds of observation and interpretation in a mediated exhibit experience.

Insights From Expert Interviews and Inquiry

One of the insights that emerged from this design elicitation was the curator's need to not only examine petroglyph scenes contained within a single panel, but also to make connections between images from different sites to illustrate, for example, distinct carving tools and techniques, evolving representational strategies, or changing depictions of animal assemblages over time. To interpret the sometimes ambiguous figures depicted in the rock art, she frequently referenced modern-day animal images as analogues to help differentiate a leopard from a cheetah form, or to compare the great size and shape of ancient auroch horns to their domesticated descendant, the long-horn cattle. She noted the importance of finding ways to help museum visitors notice fine details, pick out salient features, and make comparisons and personal connections to topics of interest. These conversations provided ideas for interesting ways to mediate, tell stories, and help users begin to look at petroglyphs with the eyes of an archaeologist.

Understanding User Interactions with a Gigapixel Image Viewer

To study user interactions with an explorable high-resolution image environment, we began by examining a pre-existing online gigapixel image viewer used in Dr. Olsen's Arabian Rock Art Heritage website to display petroglyph panoramas. To create an exhibit-like setting, we set up a 50" plasma display with an attached touch panel module to support single-touch inputs. The embedded user interface included a set of simple navigation elements for zooming and panning on one side, and a series of snapshots along the bottom edge that would trigger zooms into the selected image sub-section with brief interpretive text provided (Figure 2).

To assess the appeal and usability of this online viewer design, we used a standard think-aloud technique to observe and log user interactions (Lewis & Rieman, 1993).

A total of 23 museum visitors were asked to participate and encouraged to talk about their experience while using the gigapixel viewer and respond to questions about the interface, navigation, and content presentation.

Each user group was also invited to participate in a subsequent card-sort activity to explore content themes, preferences, and ordering (Nielsen & Sano, 1995). Here, participants were given a number of topic cards showing an image or petroglyph figure associated with a subject theme (e.g. hunting, art & craft, animals, culture) that had been drawn from our curator interviews. They were then asked to rank the cards from most to least interesting and provide reasons for their choices (Figure 3). Participants were also asked to note any questions that they had relating to themes, and to suggest additional topic areas of interest.

FIGURE 3. Sample topic cards used in the card-sort activity.

FIGURE 2. Embedded online gigapixel image viewer.

Insights From Visitor Think-Alouds

These user studies generated several key insights about the interaction and information design challenges associated with gigapixel image viewers. Participants, in particular older individuals and groups, found navigating the single touchscreen-based image viewer to be non-intuitive and somewhat frustrating. Younger audiences expected the touchscreen to support familiar multitouch scroll, pinch, and swipe inputs. These younger users adapted more quickly to the interface navigation elements. Nevertheless, poor single point touchscreen responsiveness led most users to rely on zoom sliders, snapshots, and button controls for navigation, which many felt were cumbersome and sluggish. Many users resorted to using snapshot selections to navigate. Users, especially younger ones, would often walk away from the exhibit display if they found it difficult to control.

FIGURE 4. Existing M is for Museum exhibit set-up.

We found that the existing user interface did not encourage free exploration of the petroglyph scenes, nor support observational talk and gesturing about what was seen in the image. Users reported that the system gave them no sense of how to explore the image, or any kind of contextual information about the petroglyph site. In general, most of our participants wished for more interpretive and explanatory content, in addition to the brief, purely descriptive label text. Younger audiences repeatedly expressed a desire for more engaging audio-visual or interactive media to obtain information on particular image details or themes, while older audiences indicated that more in-depth textual information and visual supplements like photographs or illustrations would help make the exhibit more engaging. As a result, the final design included images, audio, video, and text to appeal to multiple audiences.

Insights From Visitor Card Sorts

Several important insights emerged from the card sort activities. Many of the participants' responses revolved around a desire for more background information and interpretation. For instance, when shown a mural of a bow hunter with leashed dogs pursuing wild cattle, some users wanted to know more about hunting strategies in the Neolithic period. Others raised questions about the significance of the site, the rock art carving techniques used, or queried about the characteristics of stone age cultures, religious practices, or the geologic aspects of the site. We were able to use this information to identify popular and particular themes of interest (e.g. Neolithic culture, hunting). In addition, participants expressed a clear desire to have more control over how to explore content. They made requests for a more organized or structured approach to the information, and they wanted to hear specifically from the curator about points of interest within the petroglyph image. These findings guided our concept development and information design process in the next phase.

Conducting a Heuristic Evaluation of the Museum's Existing Gigapixel Viewer

Next, we wanted to assess the functionality, aesthetics, and information design of an existing kiosk-based gigapixel image viewer that had been developed for the Museum's M is for Museum exhibition (Figure 4).

The M is for Museum viewer was designed to showcase seven different GigaPan images that included both artifacts and specimens from selected from the museum's collections The gigapixel image viewer provided simple navigation elements, including a zoom/pan slider control on the left side of the image. Below the image was a row of snapshots with short text annotations that, when selected, zoomed into a key frame within the image, with a set of arrow buttons to select between images (Figure 5A and B). We used a modified heuristic evaluation and a structured visitor observation protocol to assess the usability of the installed exhibit (Nielsen, 1992). Twenty-two users were observed at the exhibit; we recorded their age, who they came with, overall engagement time, engagement time per image, and usage patterns over time.

Insights From Heuristic Evaluation

The heuristic evaluation conducted by the research team identified several common usability issues, and provided functional explanations for many of the difficulties users reported and those we had observed in earlier studies. We found best practices for usability had not been well-applied; for example, grouping icons with related functionality and

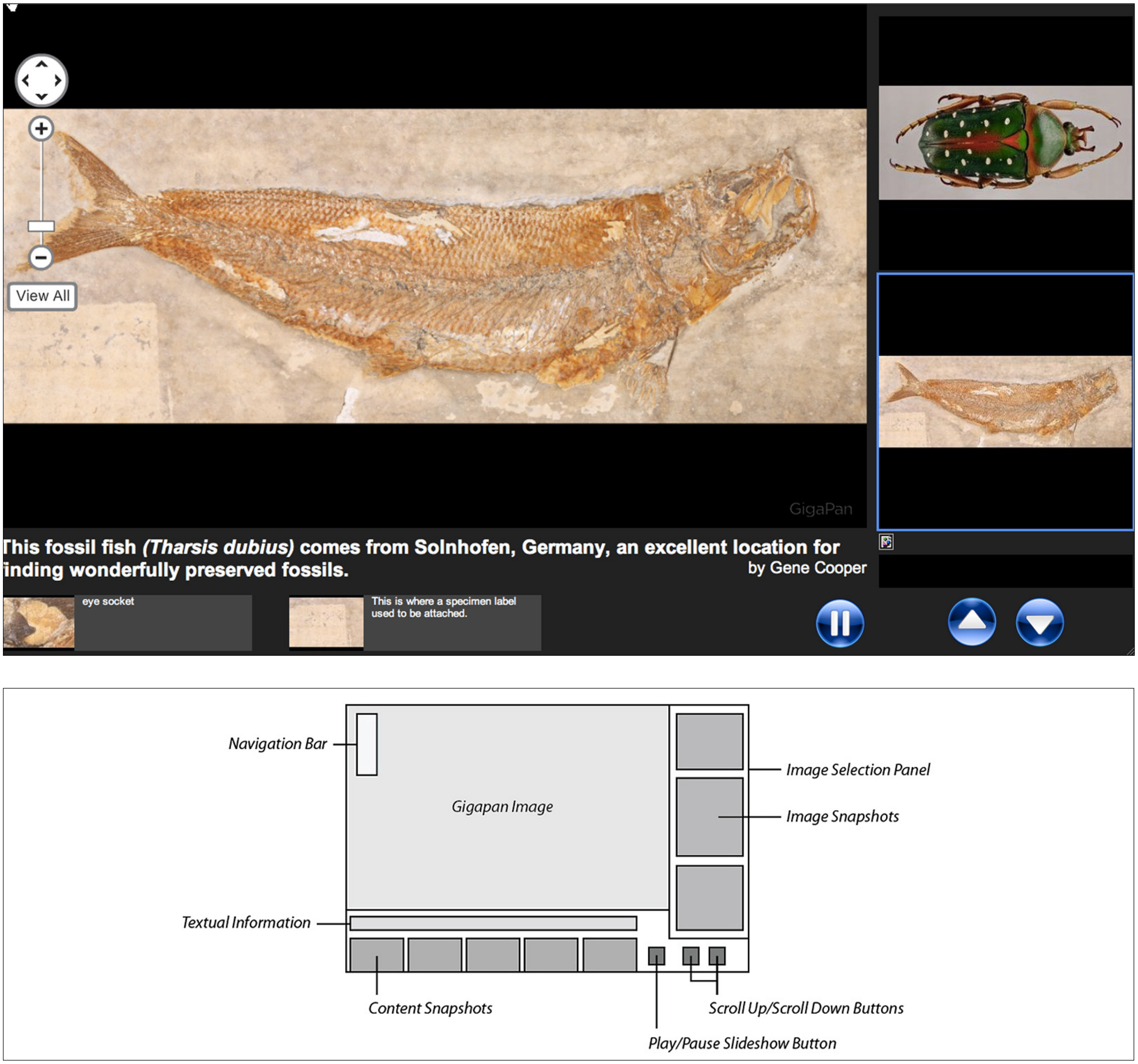


FIGURE 5A and B (top to bottom). M is for Museum Gigapixel image viewer (A) and wireframe of viewer UI elements (B).

avoiding ambiguous or non-intuitive controls. Additionally, we felt that the user interface elements took up too great a portion of screen real estate, obscuring the central photographic image, and that there was unnecessary redundancy in the way multiple interface elements performed similar tasks.

From an information design perspective, the snapshot annotations were located around the perimeter of the image, separating the close-up details from text and other potential mediation. More subtly, there was no organizational logic for the selected snapshots, no indication of what kinds of information different snapshots linked to, nor cues for how regions within the gigapixel image might be related.

Finally, we found that the text descriptions associated with the snapshots were overly brief, giving little scientific explanation, background, or interpretive clues about what to observe.

Synthesis & Design Implications

The insights gleaned during this exploratory phase, in combination with the design precedents described above, guided our concept development and experience design process in the next phase. A summary of our guiding synthesis statement follows:

- Simplify and improve the **interface usability** and **aesthetics** with support for intuitive and responsive multi-touch gestures; test different minimalist approaches to navigation and content control

- **Streamline navigational elements** in order to **maximize the screen area** available for image viewing and exploration
- **Structure content** to guide disciplinary observation and deepen exploration and discovery; **establish a clear visual hierarchy** and information ordering, revealing what type of content is available, and where it lies spatially within the explorable image
- Enhance contextual **annotation functionality** to incorporate **multimedia content** (audio, video, graphics) overlays with text to support engagement and learning
- Frame the experience as a **mediated conversation with a knowledgeable guide**
- Develop **customized learning analytics** to track user sessions, UI usage, content plays, and support summative evaluation

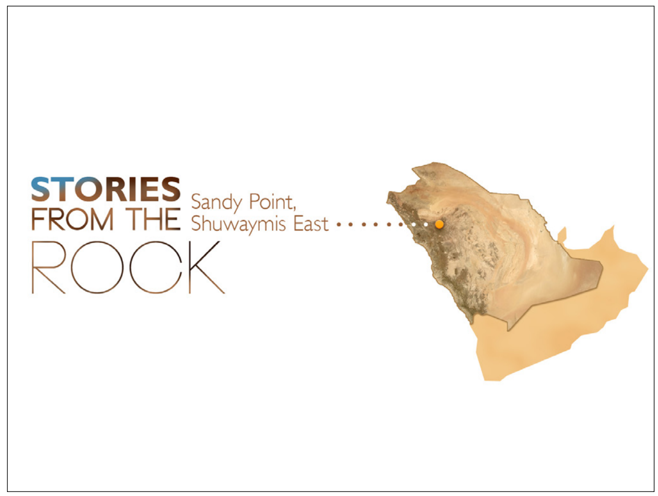
PHASE 2 | Concept Development

The objective for the next phase of work was to generate design solutions that addressed issues and opportunities that surfaced during the exploratory design phase. Using a set of design frameworks, described next, to develop user experience models, we produced a number of wireframes and high fidelity mockups that we tested with museumgoers utilizing standard A/B testing protocols (Nielsen, 2005). Further interface refinements were based on user feedback, narrowing down various iterations to a final prototype that would undergo full development and implementation. A working prototype was then subjected to further pilot testing via think-aloud protocols conducted in the museum by the research team, prior to final installation and assessment with our external evaluator.

Before describing some of the choices made in designing and developing mockups and prototypes, we present several organizing frameworks that served as touchstones in developing the user experience, structuring the content, and clarifying the design situation.

Defining a User Experience Cycle

User studies revealed that the biggest hurdle to enabling users to manipulate the image viewer and immerse themselves within the subject matter was the lack of a properly managed and compelling user experience. We posited



FIGURES 6A and B (top to bottom). Initial start screen mockup (A) and final start screen interface (B).

that the best way to bridge our project design goals with user and stakeholder expectations was to treat the user experience as a form of mediated conversation between an expert guide (i.e., the museum scientist or curator) and the learner. For this, we turned to studies on dialogue analysis, particularly work drawing on Erving Goffman's model of interpersonal communication (Goffman, 1963; Tang, 2007). In this model, an effective communication loop follows an "**initiate—sustain—leaving-taking**" cycle of interaction. In terms of a mediated interactive system, this requires an effort by the system to initiate contact by presenting the user with just enough information about a potential engagement to create awareness and attract an input; then sustain the engagement through a responsive user experience that provides exploratory agency and meaningful exchange without overwhelming the user with choices or content; and lastly, a leave-taking sequence that closes the loop while presenting opportunities for future interactions and dialogue. This "cycle of engagement" model informed several aspects of our design.

To entice museum visitors to approach the *Explorable Image Viewer* and **initiate** the activity, we developed an attract screen (Figure 6a) that presented basic overview information (e.g., title, site location, subject).

A/B testing revealed that some users had difficulties in understanding that the start screen was a prompt for interaction, and they preferred the actual zoomable panorama as a better indicator of the experience to follow. We added a "touch to explore" text prompt to invite use. These changes were reflected in the final prototype (Figure 6b) which was installed as part of the *Stories in the Rock* exhibit space (Figure 12).

We also introduced an activity tracker and timer within the viewer code, whereby the interface would revert to the start screen after 90 seconds of inactivity. This also served as a marker to calculate the duration of a user session in the server logs.

To **sustain** engagement, we sought ways to provide more navigational agency, support visual inquiry, and offer content choices based on user interests and location within the image. We experimented with a series of different annotation layouts, user interface elements, social media opportunities, and interaction paradigms, varying how and when rich media content like text, graphics, video, and audio would be shown at successive levels of depth within the image (Figures 7a and b).

FIGURE 7A and B (top to bottom). Edge-bound UI elements with an interest spot pin marker and annotation overlay separated (A). Zoomed in view of an annotation overlay encircling a region of interest (B).

We then considered sharing, commenting, and saving/embed functionality as potential leave-taking transactions to complete the user experience cycle.

Streamlining Onscreen Controls

After considering the cycle of interaction, we began to focus on simplifying the navigation elements and reducing the footprint of the user interface. Over three successive iterations of A/B testing with 12 users, we found we could eliminate explicit onscreen pan-zoom controls with a multi-touch surface. Drawing on touchscreen tablet conventions, we enabled three multitouch gestures: a tap to select, swipe to pan, and a two-finger pinch gesture to control zoom level. As an additional support, we provided an explanatory panel beside the touchscreen to illustrate these multitouch gesture controls iconically. Museumgoers across a wide range of ages found these gestures to be intuitive.

However, we found that adding a dual function "navmap"—that tracks a user's spatial location and zoom depth within the image, and provides a "view all" reset function—was necessary to help users orient and navigate a deep zoom space. Observations showed that once multitouch navigability was incorporated into the interface, users relied less on explicit interface elements, and in the final iteration, only the essential navmap and dynamic overlays were kept.

Scaffolding User Observation through Nested Content

Our user studies established that users want help in identifying what kinds of information are available, while having agency in the exploration of the image, and control over when information is presented to them. This need aligned both with our mediated conversation goal to sustain just-in-time interest-based exchanges, and the curator's request to find ways to scaffold and direct user attention to facilitate observation and interpretation.

A unique feature of high-resolution multiscalar image spaces is the two distinct ways for structuring content: one lies at the surface of the screen and offers familiar kinds of graphic design opportunities for content layout, while the second lies within the image space, where information can be located depth-wise in the form of interest point annotations or hotspot marks and revealed through user exploration and zooming. The clustering of interest spots within a region becomes an additional visual cue for information. Activating these visuospatial or perceptual modes of content organization enable new ways to organize content and provide a powerful way for users to explore more deeply based on personal interests.

Drawing on Richard Saul Wurman's information-organizing principles, we identified **location** (i.e. petroglyph sites, maps), **chronology** (i.e. time period, era, palimpsest layers), **categories** (i.e. disciplinary topics or themes), **hierarchy** (i.e. alphabetical, trophic levels) and **continuum** (i.e. rarity, popularity, size/scale magnitudes) as potential ways to structure the information design (Wurman,1989). We considered additional organizational filters such as annotation/mediation type (e.g. text, audio, video, graphic) and audience type (e.g. children, families, adults, school groups) as further ways to order content. Sorting by location, date, frequency, and type is central to the ways that scientists observe patterns and discover anomalies, allowing content to be accessed by other filters, such as child-friendly or media type, and tailors the system to a diversity of interest-based explorations of the subject matter.

To assess various information design directions we developed three different content structuring regimes to see how annotations and the corresponding mediation would function. For example, we developed mockups testing the use of a top menu bar that would give users a choice in how they wanted to sort through content, allowing them

FIGURE 8. Initial mockup showing a chronological approach using a timeline to select a date.

FIGURE 9A and B (top to bottom). Final interface showing Themes and corresponding Interest Point (A); Selected Interest Point zoomed in with media annotation overlay (B).

to select a meta-structure following one of our identified organizing principles, as we explored how content would be indexed within that structure (Figure 8).

For thematic content, we created several different solutions, testing various modes of interaction, the layout and animation of interface elements, and further explored design variables including color, shape, and iconography to denote distinct categories of information.

After evaluating screen prototypes through A/B testing and think-aloud protocols, we found that museum users responded most favorably to a retractable "themes drawer" on the left side of the screen, with a single color denoting a "selected/unselected" theme, so the corresponding "interest spots" would reflect the chosen theme color and indicate the location and distribution of that theme within the image. This solution was fully implemented for the final prototype (Figures 9a-b).

Redefining Mediated Annotations

Next we focused on how best to annotate content in a dynamic multiscalar image. We proposed that point annotations, whether text or media, are a powerful tool to reveal contextually relevant information within a zoomable visual environment. The first museum gigapixel viewer used a snapshot metaphor where a key frame from within the image served as the navigation and annotation element. The problem with snapshot interface elements is that by separating thumbnail key frames from their spatial location within the image, the information is dislocated from its subject, and hard-to-see details within the snapshot area are not pinpointed. Moreover, framed snapshots are poor markers of significance, and provide no easy indication of the spread, density, and relationship between annotated areas.

We chose to explore an "interest spot" metaphor as a more precise way to pinpoint and contextualize multimedia annotations within a multiscalar zoomable user interface. Interest spots act as both a specific marker of where visual details lie as one zooms in, and become points around which content overlays anchor and present on screen. Our experiences suggested that these point annotations offered a flexible and compelling information design strategy.

Across several design iterations, we tested the idea of layering interest point icons with additional functionality and choice, giving users control over content modality, links to external sources, and access to social media via share buttons (Figure 10). We also considered supporting "interest spot"-based conversations between the public

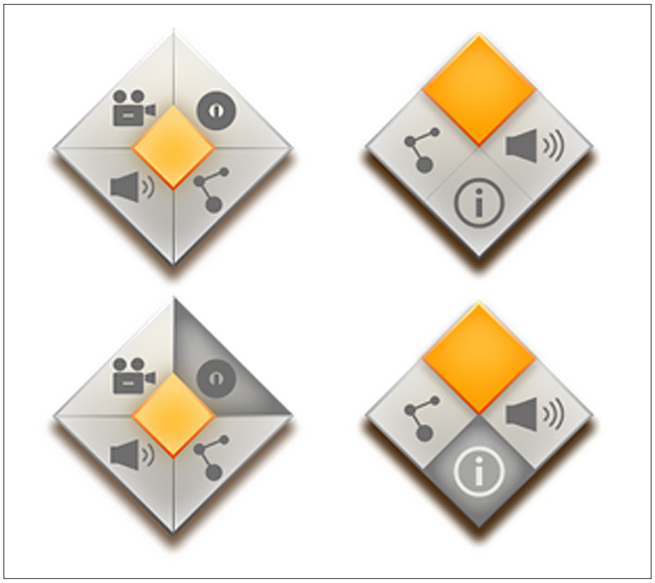


FIGURE 10. Enhancing interest points with added contextual functionality.

FIGURE 11. Museum visitors at the *Explorable Image Viewer*.

and the museum staff. These strategies would enhance the mediated conversation and leaving-taking aspects of the interaction cycle. However, due to project scoping requirements, museum capacity, and time constraints, we avoided development of these enhanced interest points in the final prototype. It is worth noting that over the course of user testing, participants generally liked the idea of this added functionality, suggesting that this is a promising area for future investigation.

PHASE 3 | Implementation & Evaluation

Throughout the design process, we worked closely with our technology partner, the CREATE Lab at Carnegie Mellon University, to both generate and vet ideas and to understand the software engineering implications and feasibility of design choices. The final prototype system needed to withstand the demands of a museum setting, which imposed several technical constraints: the system must run with minimal maintenance; it had to run locally without an Internet connection and cloud storage; and it should self-recover from a crash.

The final design was implemented in JavaScript and HTML5, and rendered in the Mozilla Firefox web browser running on Windows 7 Pro 64-bit. Because all assets were stored locally, the kiosk computer ran a local instance of the Apache HTTP Server to which the web browser connected to load all content for the interactive display. Running the assets locally resulted in faster access times for a better user experience, while also obviating the need for network maintenance, and reducing memory leaks and crashes, which ensured that the viewer ran with minimal maintenance or down time.

The gigapixel image viewer was created using a modified version of Microsoft Seadragon Ajax, which supports loading gigapixel images, making use of several open-source JavaScript libraries including jQuery, Hogan, and Less. We also selected hardware to provide an optimal, lag-free user experience, utilizing a quad core Intel i7 CPU, 8 gigabytes of RAM, and a solid-state hard drive for reliable and fast access to the image files, and an economical Planar 24" multitouch screen installed in a custom freestanding kiosk.

As part of our customized learning analytics, the viewer incorporated an event tracking system which recorded every user action, gathering exact statistics on which parts of the gigapixel image were most explored, when audio/video elements were played, and active usage time vs. idle time. The data was compiled and visualized using a combination of custom web server log analysis and Google's Fusion Tables software.

In order to test the effectiveness of the new viewer in the context of an exhibition setting, we contracted with Laser Labs, a local design and fabrication studio, to develop supporting prototype elements for the *Stories in the Rock* exhibit environment, including a modular display wall for a large GigaPan print of the archaeological site, wall panel graphics, and kiosks with "stone phone" audio handsets (Figure 12). With the museum education staff, we also jointly developed a set of tabletop rock art tracing and card matching activities for families that simulate techniques and practices archaeologists use to observe and interpret rock art images.

The exhibit launched in late November 2012 and was installed for five months at the Carnegie Museum of Natural History. Stool seating for 2-3 people was made available to encourage collaboration and increase exploration time (Figure 11). The *Explorable Image Viewer* developed for the

FIGURE 12. GigaPan of the Stories in the Rock Exhibit Space.

exhibit is available online at sitr.gigapixelscience.org for updated versions of Google Chrome or Mozilla Firefox, and the interactive is best viewed at its native 1920x1080 resolution.

Summative Evaluation Findings

We collaborated with an external evaluator, Rockman et al, to assess the learning and engagement impacts of the project. In particular, we wanted to understand if the design engaged users, and whether it supported observation and noticing with the "eyes of an archaeologist." Evaluation methods included:

1. iForm Timing & Tracking Observations (~60)
2. *Explorable Image* videotaping (~20 adult, ~20 family)
3. Exit Interviews (~25)
4. Custom Server Log Learning Analytics (~1900)

While we are currently in the process of synthesizing both qualitative and quantitative findings from video data, initial observation, interview, and learning analytics findings have yielded promising results. Log file data from December 1, 2012 through March 20, 2013 was searched to identify patterns in how visitors were using the *Explorable Image Viewer*, and revealed that a number of visitors used the kiosk; 1,928 sessions were logged during this period. Data from February 7, 2013 was removed from the system due to a computer glitch. Daily Usage Statistics indicated that an average of about 21 users per day interacted with the exhibit. Actual usage may have been greater, since the system could not differentiate sessions when one user left and another user immediately sat down to engage with the *Explorable Image*. The average number of users was greater on weekends (N=30) than on weekdays (N=16), as would be expected based on museum visitation patterns (Sandifer, 1997). Users spent an average of 3 minutes and 38 seconds at the interactive exhibit, a lengthy time by museum standards (Naqvy, Venugopal, Falk, & Dierking, 1991; Yalowitz & Bronnenkant, 2009). Weekend visitors spent slightly more time with the viewer (M=3 minutes, 56 seconds) than weekday visitors (M=3 minutes, 20 seconds).

Observations revealed that adult-only groups spent more time at the kiosk than families; however, both groups were equally likely to approach the interactive. Groups with children also tended to freely explore the image most often, while adult only groups were more likely to use the *Themes* and click on the audio/video overlays. Taken together, these findings indicate that visitors were attracted to and used the *Explorable Image*, they engaged with it for prolonged periods of time, and their interactions with the technology differed based on who they came to the museum with and which day they visited the exhibition.

Based on exit interview data, we were also able to address the appeal of the exhibit: 50% of interviewees (N=16) indicated that they were drawn to the exhibition specifically by the *Explorable Image Viewer kiosk*. Regardless of their reasons for approaching the exhibition, almost all interviewees (90%; N=30) who visited the kiosk indicated that it had been their favorite part of the exhibition. Most (70%; N=27) felt that the interface had been easy to use, likening the experience to that of a smartphone or Apple iPad.

In addition, the interviews provided some initial evidence that the interactive had supported learning, observation, and noticing behaviors. All interviewees who were asked (N=23) agreed that the technology had helped them look at and understand the petroglyph image in a deeper way. In fact, almost all users (96%; N=24) reported being able to identify a carved figure in the petroglyph. Furthermore, most users (93%; N=29) were able to identify ways in which scientists use imaging technology in their research. Further analyses are currently being conducted looking at users' videotaped

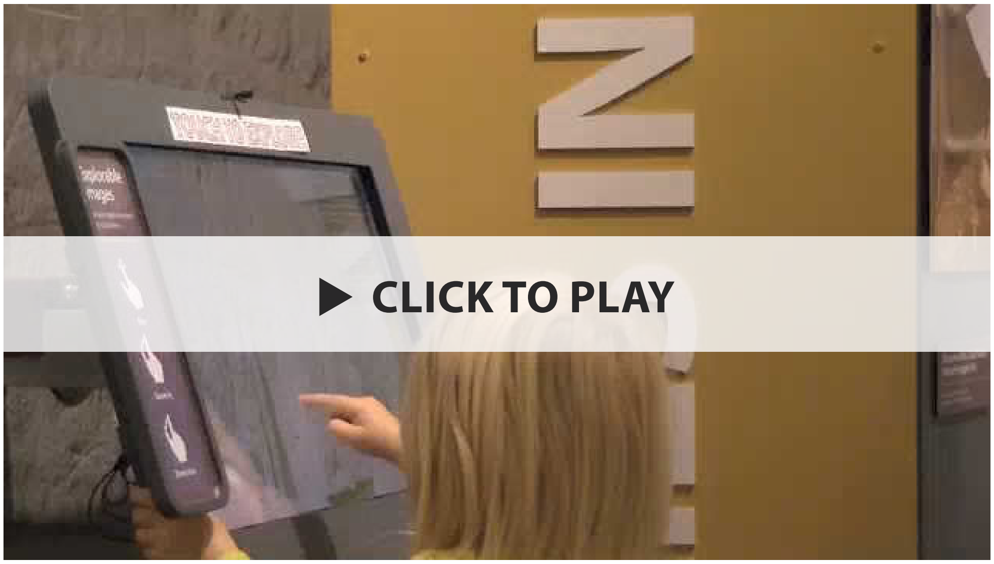


FIGURE 13. Video of parent-child interaction and observational talk at the *Explorable Image Viewer*.

FIGURE 14. Usage data for user interface elements.

interactions to determine the extent to which the design supported observation-related conversations and gestures (Figure 13).

We were also interested in how users were exploring the interface, accessing and engaging with content. The viewer allowed users to either freely explore the image, select a theme, or tap on an interest spot to find out more information.

Our log data shows that the *Interest Points* were the most frequently used screen element (43%); *Themes* were second (38%); and the top left *Nav Window* (+view-all function) was used least (19%). *Interest Spot* selection tended to be from left to right, with those on the left hand side of the screen being chosen most often. This pattern may indicate that users were approaching Explorable Image viewing like a book. *Themes* selection was fairly evenly distributed across the five topics categories. When *Themes* were selected during a user session (75% of the time), *Hunting Scenes* were chosen most often (23%), followed by *Prehistoric Animals* (21%). *Climate Change* was selected the least (16%). This top to bottom vertical usage may reflect interest or perhaps location convenience (Figure 14).

In terms of text and media content usage, our exit interviews with users revealed that 96% of interviewees (N=26) read on-screen text; Many (76%) felt that the text had provided helpful information. Several interviewees (65%; N=23) also indicated that they had listened to the audio or video. Of these, most (92%; N=13) felt that the audio and video had provided helpful information.

Log server analysis over the five-month time period showed that when media was available in an *Interest Point* overlay (audio/video), it was activated 21% of the time (N=1928). Our log server analysis also gave us fine-grained data regarding media activations and drop-offs per *Interest Spot* overlay, indicating the general appeal and relevance of different media that will inform the editing and inclusion of embedded audio, video, and graphics as we develop this aspect of the design in future iterations.

FUTURE DIRECTIONS

Our design research and evaluation findings indicate that the newly developed *Stories in the Rock* exhibit successfully met many of the project goals. User engagement with the explorable gigapixel image viewer has increased with each prototype, both in terms of the average length of user session times and in the use of supporting text and media annotations. Based on preliminary observational data and interview findings, the experience appears to be increasing scientific forms of observation and talk, and users are better able to explore the subject matter based on their personal interests. The video coding currently being conducted with Rockman et al will further deepen our understanding of whether engagement, observation and learning goals have been met.

The design team, in close conversation with our museum partners, identified the following next steps as high priority:

1. Refine/add content to increase observational talk and media plays
2. Make content more child-friendly, consider "I Spy" type hide-and-seek games
3. Improve "leave-taking" aspects of the user interaction, and ways to extend the conversation
4. Add purposeful sharing and dialogue tools
5. Leverage scale and the resolution available through bigger displays (i.e., projection, larger screens)
6. Experiment with gesture-based inputs and other kinds of emerging natural user interfaces
7. Develop a general purpose museum research and collections viewer

We also want to highlight several promising directions. Enhancing annotations with additional functionality is certainly something that requires development and further user testing. We also feel that the current prototype did not fully exploit the opportunity to use the gigapixel image platform as a social media space where joint viewing and conversation can occur online and asynchronously (Takeuchi & Stevens, 2011). As we continue to develop this system, we will look for ways to support more direct engagement and discussion between museum experts and communities of learners—and following Goffman's cycle of engagement—to sustain dialogic exchanges. Currently no functionality exists for leaving comments or observations within the multiscalar image space, or for sharing information via social media channels, and these possibilities merit further exploration. Adding the ability to share or tag content that users found particularly interesting, would also help to strengthen the leave-taking aspect of the user experience cycle that we have proposed, giving users new incentives to revisit and connect again.

While this project focused mainly on illuminating non-linear navigational control and content structure within a single gigapixel image, we note another area of need based on meetings with museum scientists: developing ways to navigate and structure content relationships between gigapixel images, and other forms of high-resolution visual data (e.g. geospatial, simulations, visualizations). Moreover, research groups are inventing ever more powerful, interactive visual browsing tools for high-resolution media. Our CREATE Lab technology partner recently developed GigaPan Time Machine, which extends gigapixel image exploration over time—adding another dimension of animation and complexity to the design space. Designers must find natural ways to interweave narrative with the free exploration of text, sound, and moving images spatially over time, and establish graphic conventions for enabling social and interpretative activity in these kinds dynamic visual environments.

There is also considerable interest in using gigapixel image technology to bring other aspects of museum research and collections to the public. We would like to develop a content management system for museum scientists, and more generally the public, to be able to easily create and manage their own digital annotation overlays.

Our hope is that the compelling visual nature of these networked, explorable image environments evolves into a fully realized cyberlearning infrastructure that deepens observational practices and rich exchanges between professionals and publics in a shared visual environment that is accessible to all.

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