Living Liquid: Design and Evaluation of an Exploratory Visualization Tool for Museum Visitors

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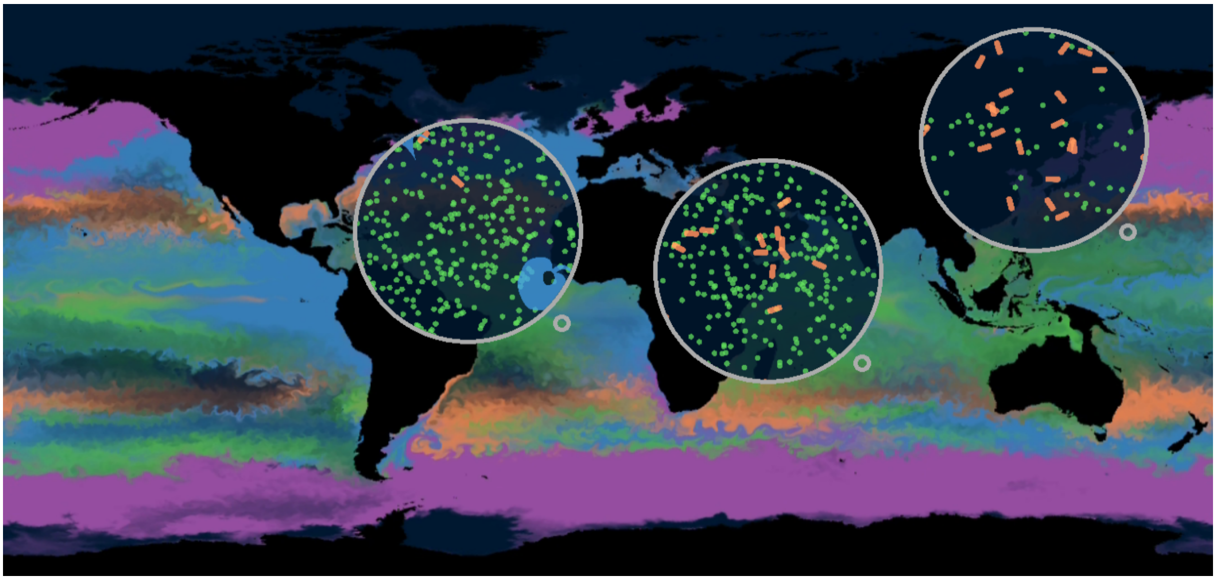

Fig. 1. Living Liquid allows museum visitors to explore global phytoplankton distributions across time.

Abstract—Interactive visualizations can allow science museum visitors to explore new worlds by seeing and interacting with scientific data. However, designing interactive visualizations for informal learning environments, such as museums, presents several challenges. First, visualizations must engage visitors on a personal level. Second, visitors often lack the background to interpret visualizations of scientific data. Third, visitors have very limited time at individual exhibits in museums. This paper examines these design considerations through the iterative development and evaluation of an interactive exhibit as a visualization *tool* that gives museum-goers access to scientific data generated and used by researchers. The exhibit prototype, Living Liquid, encourages visitors to ask and answer their own questions while exploring the time-varying global distribution of simulated marine microbes using a touchscreen interface. Iterative development proceeded through three rounds of formative evaluations using think-aloud protocols and interviews, each round informing a key visualization design decision: (1) what to visualize to initiate inquiry, (2) how to link data at the microscopic scale to global patterns, and (3) how to include additional data that allows visitors to pursue their own questions. Data from visitor evaluations suggests that, when designing visualizations for public audiences, one should (1) avoid distracting visitors from data that they should explore, (2) incorporate background information into the visualization, (3) favor understandability over scientific accuracy, and (4) layer data accessibility to structure inquiry. Lessons learned from this case study add to our growing understanding of how to use visualizations to actively engage learners with scientific data.

Index Terms—Information visualization, user interaction, evaluation, user studies, science museums, informal learning environments.

1 Introduction

Interactive visualizations can be exciting new additions to science museums, allowing visitors to investigate new worlds by exploring scientific data. They provide the visiting public an accessible means to investigate data (visually, rather than textually or analytically), to make observations, detect patterns, generate hypotheses, and make discoveries. Visualizations also allow visitors to look at large datasets using tools and methods similar to those actually used by researchers, and therefore provide museum-goers authentic exposure to the process and practice of scientific discovery.

However, designing interactive visualizations for science museums presents several specific challenges:

- Museums are free-choice learning environments where visits are largely motivated and guided by personal interests. Creating visualizations that are appealing and engaging is critical to how they are used, and if they are used at all.
- Museum visitors come with varying levels of content knowledge. Visualization designs, therefore, should be meaningful to both novices with nascent understandings of the subject area, as well as experts with deep domain knowledge. In all cases, visualizations must remain authentic to the underlying science.
- Visitors may not be familiar with the visual representations used

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in a particular domain, or possess the expertise required to relate them to concepts in the scientific field. Therefore, museum visualizations, if not familiar to lay people, should be intuitive and easy to decipher.

- Visitor time at any given exhibit is on the order of minutes or seconds, so extensive training in visualization usage is infeasible in the museum context. Thus, visualizations should be designed to allow visitors to rapidly explore, find patterns in, and make sense of the data.

This paper examines the challenges in designing an interactive visualization tool to support inquiry at science museums by documenting the iterative development and evaluation of Living Liquid, an exhibit prototype that allows visitors to explore the simulated global distribution of marine microbes. Developed at the Exploratorium in San Francisco, a museum of science, art, and human perception, Living Liquid will be one of only a few science exhibits that use visualization as a tool for investigation. As such, its development presents a unique opportunity to formulate design constraints for visualization tools in museums and to discover possible solutions. More broadly, this work contributes to our growing understanding of ways to engage learners with current science through visualization of research data.

2 Related Work

2.1 Visualizations in Science Museums

Prior work by Hinrichs [20] and Viégas [45] introducing information visualizations to art galleries have elucidated challenges similar to those listed above. However, to date little has been done in designing visualizations for science museums that give visitors access to scientific datasets used by researchers. Despite the increasing reliance of science on visualization tools, only a handful of informal science organizations are exploring ways of visualizing scientific data. These include NOAA's Science on a Sphere network, the Future Earth project at the Science Museum of Minnesota, Adler Planetarium's Visualization Laboratory, the Tahoe Environmental Research Center Visualization Lab, and the NISE Visualization Lab. So far, visualizations in science museums have largely been used as "visual explanation tools" [24] to display data that impart specific messages about scientific content, or to provide ways to browse through large, curated databases [21, 19].

There has been less work looking at developing "visual data analysis tools" [24], or visualization tools; that is, making exhibits that allow visitors themselves to explore large scientific datasets and engage in inquiry. One example is the Rain Table at the Science Museum of Minnesota, where museum-goers can interact with "two-dimensional maps of the Earth on a large high-resolution digital table, select locations of rainfall [using electronic pucks], and then watch as the rain flows down mountains and across fields, cuts channels through slopes and plains, and floods streams and rivers."[37] Because Rain Table uses a mathematical simulation model that scientists use, it authentically exposes visitors to tools and data that researchers themselves are using.

2.2 Visualizations in the Classroom

One promising strategy in engaging museum-goers with scientific data is to provide them with a visualization tool with which they can ask and answer their own questions with the dataset. Previous work in developing visualization tools for learners to explore large scientific datasets have largely targeted the classroom setting [35, 9, 42, 39]. Based on work with middle school and high school students, Edelson and Gordin [8] proposed a framework for adapting scientific visualization tools for learners. Many of the challenges identified in this framework broadly apply to both the formal and informal learning environments. These include:

- creating a motivating context that is personally meaningful,
- selecting datasets and activities that enable learners to ask and answer their own questions, and
- designing an interface that supports and builds understanding.

This framework represents a good starting point for the creation of visualization tools for museums. However, there are key differences between formal and informal learning environments that make direct application difficult. How these guidelines were adapted and refined for the museum environment are discussed here through a case study of the design and iterative development of Living Liquid.

3 Living Liquid

Living Liquid is an exhibit prototype developed at the Exploratorium, in collaboration with the Visualization Interface and Design Innovation (ViDi) group at the Universtiy of California, Davis, and the Center for Microbial Oceanography Research and Education (C-MORE). The exhibit aims to actively engage visitors, 11-years and older, with emerging research about the ocean's microbes by providing visitors with a visualization tool with which to explore data about ocean microbes and their environment.

3.1 The Museum Context

Museums are a particular type of informal learning environment referred to as designed environments, in which exhibits are developed and interpreted by the museum to help structure visitor experiences in line with institutional goals and values [34]. As with other types of informal learning environments, the experience in museums, as compared to the formal setting of the classroom, is motivated and guided by personal interests rather than compulsory requirements [14, 10]. In other words, museums are free-choice environments where visitors choose which exhibits to use and how to use them. Visitors at museums may see only a fraction of the exhibits and pay close attention only to those that are of particular personal interest to them [40]. Even in the case of a single exhibit, any given visitor may only attend to a certain aspect of the exhibit that is meaningful to him or her.

The exhibit experience itself is often characterized as *unmediated*, *episodic*, and *short*. First, many science exhibits are designed to be *unmediated*, or stand-alone, to be used without staff facilitation. Physical affordances and labels are typically the only means to guide interaction and to interpret content for visitors, many of whom may be unfamiliar with the underlying scientific principles, collected data, and visual representations used by researchers in the field.

In addition, exhibit experiences are *episodic*. Exhibits do not sit in a larger "curriculum" in which one exhibit depends or builds upon the previous exhibit experience. Visitors will use an exhibit only once or perhaps a few times in their lives, with little continuity between uses. Connections between different exhibits also tend to be loose. This is especially true for an open floor plan, where the physical layout does little to sequence exhibit experiences. Co-dependent exhibits are also harder to maintain, since they require every exhibit in a set to be operational for every other exhibit in the set to work. Consequently, many exhibits are designed to be self-contained experiences, making cursory, if any, reference to other exhibits. We cannot assume that a visitor comes to an exhibit with "pre-requisite" knowledge gained from prior uses or other exhibits.

Furthermore, each exhibit experience tends to be *short*. Holding times for exhibits are measured in minutes, or even seconds. For example, in the Life Sciences area of the Exploratorium, visitors on average spend just over 30 seconds at each exhibit [18]. Exhibits designed specifically to promote active, prolonged engagement average about 2 minutes and 10 seconds [23].

The above characteristics are common to many science museum exhibits and present design challenges to any visualization created for such a setting. In the next section, we discuss how these characteristics inform the design of Living Liquid.

3.2 Design Requirements

The science museum context, and the Exploratorium in particular, imposes certain constraints on designing visualization tools for exhibits. First and foremost, because a museum is a free-choice learning environment, visualizations in a place like the Exploratorium must appeal

Fig. 2. Wordle visualization of the places visitors would like to explore for tiny marine organisms. The relative frequency of a term is represented by its relative height.

to and engage visitors. In contrast to interactive visualizations developed for expert practitioners, which are often designed according to efficiency-based theories and evaluated based on their usefulness in completing tasks quickly [22], visualizations designed for museums can be engaging for a variety of reasons, such as aesthetics, novelty, and what it allows visitors to see and do. A good design allows multiple ways for different visitors to become interested in the visualization and what is visualized. As a visual tool, Living Liquid should engage its users on a personal level.

Second, museum visualizations should be readily understandable. There is no training period at a museum exhibit and often no staff to help a confused visitor, who will easily give up and move on to the next more exciting, less frustrating exhibit. Because many visitors are not domain experts, visualizations should be understandable to people who are new to the scientific content, while remaining authentic to the underlying science. Likewise, if a visualization is not already familiar to the lay person, it should be easy to decipher. For Living Liquid, this means that visitors should be able to make sense of the scientific data being visualized without staff facilitation.

Although there are many ways in which visualizations can be used in a museum, we chose to consider ways of using visualizations as exploration tools. This approach aligns with the Exploratorium's pedagogical strategy to develop experiences that spark curiosity and empower visitors to make discoveries of and on their own. Inquiry is a powerful process for learning in informal science education [16, 34]. A visualization that can encourage visitors to ask their own questions of the data and allow them to pursue their answers with the dataset, can provide a meaningful learning experience in museums. Like visualizations designed for experts, such visualizations should allow their users to examine variables, see patterns, make correlations, ask and answer their own questions, and examine and make sense of the data.

However, as previously mentioned, tools need to be designed so that a visitor unfamiliar with the science, the data, and visualization can explore meaningfully. In addition, although we hope that visitors will have the interest to drill down into data, visitors should also be able to find something meaningful even with cursory interaction, given the short holding times at exhibits. For Living Liquid, this means that visitors, who can step away at any time, nonetheless look at the different types of information in the dataset, see patterns and make correlations in the data, generate their own questions about the data, and answer their own questions with the data.

In the remainder of this paper, we describe how Living Liquid was conceptualized using these initial requirements, and refined through an iterative prototyping process. Throughout development, formative evaluations with Exploratorium visitors were conducted to gauge how interesting visitors found the visualization, how understandable was the data visualized, and how the visualization supported exploration. Results were then used to inform design changes for successive iterations of increasingly sophisticated prototypes of Living Liquid. These evaluations were conducted at key junctures of the prototyping process to answer design questions about (1) selecting the data to visualize to initiate exploration, (2) adding a complementary visualization, and (3) layering of additional variables.

3.3 The Dataset

The ocean is a living liquid, each drop filled with millions of bacteria, viruses, and other microbes [1, 7]. These tiny creatures are responsible for life on earth as we know it: They produce half the oxygen we breathe, spur the formation of clouds that cool our planet, and absorb more carbon than all forests [44, 26]. Yet, we know very little about them [3, 12]. This is changing thanks to new data collection and analysis techniques, such as environmental genomics [2, 3, 15] and sophisticated modeling and simulation tools [11]. With these advances, researchers can begin to ask and answer fundamental questions about the ocean's microbes: What types live in each region of the ocean? Why are they there? Are they changing? What does a change indicate? Visualizations are important tools that help researchers make sense of the massive quantities of data used to address these questions.

Currently in the field, environmental genomics techniques are used to investigate select locations sampled at particular times to answer specific research questions. A comprehensive survey of the world's oceans is still outstanding. Instead, models and simulations are used to generate data about global patterns of marine microbial populations. In particular, the MIT Darwin Project has been developing sophisticated computer models of the distribution of marine microbes, simulating the population change in different types of phytoplankton over location and time [11].

The Darwin Project uses geophysical data from the ECCO and ECCO2 projects [32] and includes a rich set of variables: 78 phytoplankton species with different attributes and properties (such as growth rates that depend on environmental conditions) that can be grouped into broader types, velocity vectors of ocean currents, temperature, salinity, photosynthetically available radiation, and concentrations of organic and inorganic nutrients for every point in the world's oceans. In addition, many more can be derived from the simulation outputs (e.g. diversity, biomass, and primary production). As part of their work, the Darwin Project has generated a set of movies visualizing several aspects of the dataset [43], which provided a starting point for the Living Liquid exhibit.

3.4 Implementation

The Living Liquid interactive prototype was implemented in C# using Visual Studio 2010 and XNA 4.0 in Windows 7. At design time there was a distinct possibility that the final exhibit would be deployed using the Microsoft Surface 2 multitouch and object-tracking table. Since development for the Surface platform also uses Windows 7 / C# / Visual Studio, this choice would facilitate code reuse with minimal additional effort, should the Surface 2 be chosen for the final exhibit. Finally, the other system under consideration for touch and object tracking in the final exhibit, TUIO [25], is cross-platform and provides a C# client implementation, so we did not foresee any limitations due to our initial choice of programming language.

To make the interactive prototype easily configurable by evaluators, the Living Liquid executable loads values from a text file at runtime. This file contains over 50 parameters that can be used to adjust the program's behavior and appearance, such as the transparency, size, and count of plankton types, how long zoomed circles remain open before fading out, and whether to stop the passage of time while a zoomed circle is open.

Two open-source libraries were used in this project. EasyConfig [13] loads settings from a text file at runtime, and the 2D XNA Primitive Shapes Library [31] draws simple shapes such as circles and lines.

The prototype computer is a Dell OptiPlex 990 with an Intel Core i5-2400 @ 3.10GHz, 8 GB of RAM, and a GeForce GTX 560. The touchscreen monitor used in the prototype is an Elo TouchSystems 26-inch widescreen display. This display is large enough to accommodate one or two users at a time.

4 Visualization Design

Exhibit development at the Exploratorium follows an iterative prototyping process in which formative evaluation studies are conducted to provide timely visitor feedback to inform design. Depending on the complexity of the exhibit, a prototype may be evaluated multiple times during its development, with each successive evaluation looking at a more sophisticated version of the prototype. For Living Liquid, development was primarily concerned with creating a visualization tool that visitors found interesting, that they could understand, and that would engage visitors in exploration. Three iterations worked toward this end. The following is organized according to key design decisions made during that iterative development and evaluation process.

4.1 What to visualize to initiate exploration

As one of many interactive exhibits in a dynamic, hands-on museum, Living Liquid requires a captivating visualization to act as an entry point for exploration of plankton patterns. Previously, the Darwin Project had created different types of visualizations, including animations of global change over time, small multiples, and more traditional graphs, each of which serve different purposes for their scientific team. We sought inspiration from these visualizations but made selections and modifications for the museum audience.

We began with the Darwin Project's animations, some of which show patterns on a rotating sphere, and some of which display data projected onto 2D maps. These movies can provide the dynamism required to catch visitors' eyes, and contain patterns that can surprise, pique curiosity, and prompt questions and continued engagement. Previous experience with Science on a Sphere [33], in which animated data visualizations are projected onto a sphere, making it appear to rotate, suggests that visitors have difficulty tracking a particular location as the sphere "spins" [41, 28]. In contrast, a 2D global map can more easily initiate examination of different regions; an interview study with Exploratorium visitors found that 134 out of 136 visitors readily picked out areas of the world's oceans on a 2D global map that they would like to explore for microscopic marine life [30]. Because of its intuitiveness to visitors, and its more efficient use of a rectangular display area, we decided to use a 2D equirectangular projection for our global overview visualizations.

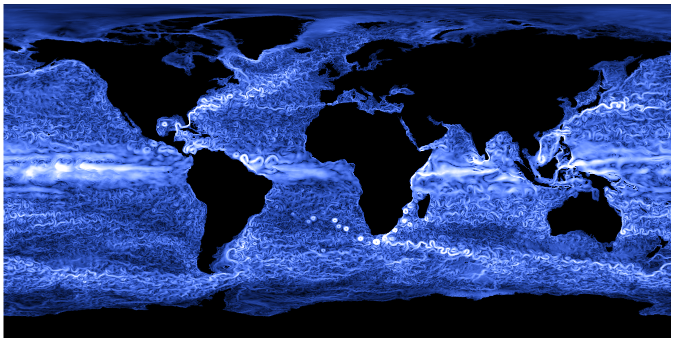
Next, we changed the color palette. Although the colors for the Darwin Project visualizations were carefully chosen for their purposes, we were concerned that some of the colors would connote unintended meaning for visitors. In an interview study of museum visitors' interpretations of nanoscale images, the Nanoscale Informal Science Education (NISE) network found that 19 out of 56 (34%) visitors misinterpreted the false color on scanning tunneling and atomic force microscopy images as temperature [29]. We were concerned that this misinterpretation would be even more prevalent with a world map, given the preponderance of global weather maps. Thus, we deliberately chose a vivid color scheme from ColorBrewer 2.0 [17], (one that excluded the bright red used by the Darwin Project) which we hoped would be less likely to be mistaken for a temperature or heat map.

Finally, we decided to show global patterns instead of data from only a few focal regions. This decision stemmed from a previous interview study's findings [30]. When we showed visitors a map of the world's oceans and asked them what parts of the oceans they would be interested in exploring, to find tiny creatures, the most frequent response was the Antarctic (28% of the 134 visitor participants in that study). It is important to note, however, that there was no single location dominating visitors' responses, as illustrated in the Wordle visualization in Figure 2.

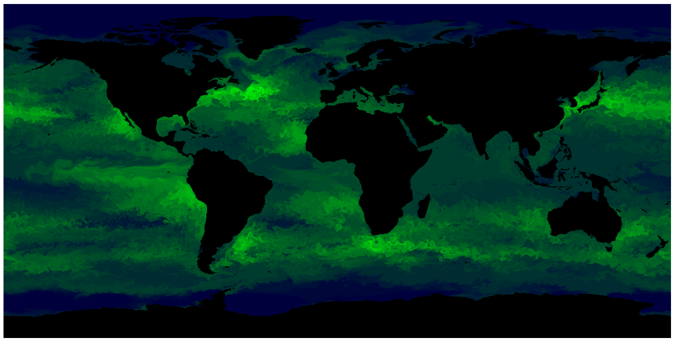
Instead, visitors found different areas interesting for different reasons. This suggests that using a dataset that focuses on only a few locations may not provide opportunities for visitors to connect the data to personal interests, and that they may not be as motivated to explore data about an area they don't know or care about. After considering the Darwin Project visualizations, we created three animations, each of which visualizes a different aspect of the Darwin Project dataset: (1) ocean currents (Figure 3(a)), (2) phytoplankton diversity (Figure 3(b)), and (3) dominant phytoplankton type for each region (Figure 3(c)).

4.1.1 Ocean Current, Diversity, and Dominant Type Movies

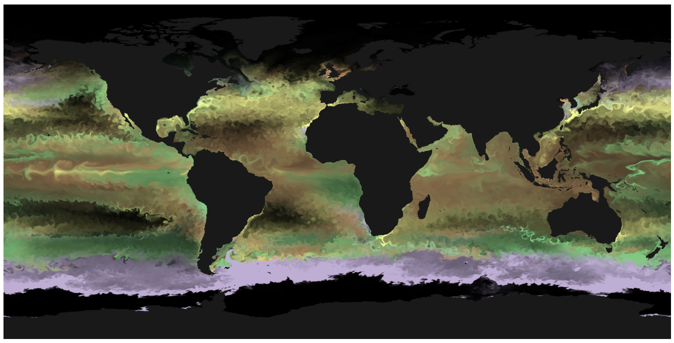
For all three movies, 2191 frames corresponding to daily timesteps for 6 years were generated using Python Imaging Library. Frames were sequenced using ffmpeg at 15 frames per second, resulting in videos lasting 2 minutes and 26 seconds each. Linear normalization was used to scale color intensities to the minimum and maximum values found in each dataset. For the dominant plankton type video, colors corresponding to each type were alpha blended based on the relative abundance of each type at each location.



(a) Ocean currents. White: high velocity magnitude; dark blue: low velocity magnitude; black: landmasses.



(b) Plankton diversity (78 different species). Green: high diversity; dark blue: low diversity; black: landmasses.



(c) Dominant plankton types at each location. Purple: large phytoplankton (diatoms); yellow: other large phytoplankton; green: small phytoplankton (*Prochlorococcus*); orange: other small phytoplankton; dark blue: no phytoplankton. Alpha value is proportional to population density for each type at each location.

Fig. 3. Several different parameters in the dataset were considered for visualization.

4.1.2 Formative Evaluation

Although these three video visualizations did not support interactivity, they provided valuable conversation pieces for soliciting visitor feedback during the early stages of development, when the question of which data subset to visualize for the public was being considered. We conducted small formative evaluations using these three prototypes with visitors recruited in the Exploratorium's Life Sciences section. Using a think aloud protocol, we collected data on:

- interest - what visitors found interesting,

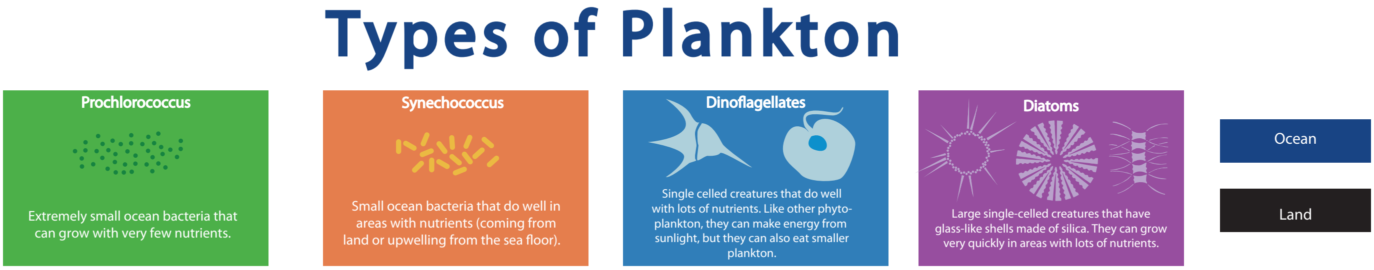


Fig. 4. Legend accompanying the second prototype, describing the four types of plankton and showing the color representations used in both the world map and the circle viewer.

- understandability - what they thought they saw, and
- exploration - any questions visitors had while watching each movie

A short interview followed the think aloud. Each visitor watched and responded to only one movie. In total, the think aloud and interview for each visitor lasted less than 15 minutes. The purpose of these small formative evaluations was to identify promising directions to pursue as part of rapid iterative development, and not to find statistical differences between groups.

Seven visitor groups, ranging from one to three visitors per group, looked at the ocean currents movie. All of the groups we spoke with remarked on the interesting patterns they saw, but four out of the seven were confused as to the type of current depicted. For example:

> *Group4_currents:* So these are currents *(pause)* of air?

All of the groups asked questions about the currents, such as:

> *Group7_currents:* The circles coming off Madagascar. How does it get into a circle like that?

However, no one asked about living things in the ocean until prompted during the subsequent interview. Even then, of the five who said they would want to look for living things in the ocean, life was but one of the many variables they wished to look at in addition to chemicals, sunlight, wind, and other physical properties.

Twelve groups watched the dominant type movie and eleven groups watched the plankton diversity movie, respectively. Some visitors found the visualizations interesting (7 out of 12 for the dominant type animation and 7 out of 10 for the diversity animation), remarking on the subject shown, the patterns, and the visualizations' aesthetics. However, visitors also complained about not having enough information to appreciate what was happening in the movies. Even though most groups thought that the visualization represented some aspect of plankton population, two groups who watched the diversity movie did not make any mention of plankton and thought the visualization was about weather or currents, and three groups (2 for dominant type and 1 for the diversity movie) thought the diversity movie showed plankton but also interpreted the moving populations as ocean currents.

Many visitors (7/12 for dominant type and 7/10 for diversity) asked their own questions that could be answered with the Darwin Project dataset. For example:

> *Group1_diversity:* Does this have to do with climate or currents?
>
> *Group10_type:* But the purple disappears? Are they just dying out or is it just at certain points? See they come back. In the middle they always stay.
>
> *Group18_diversity:* Does temperature affect them?

This was a promising indication that visitors would be motivated to further explore the data. On the other hand, close to half of the visitors also asked for more background information (e.g. about plankton life, research that scientists are conducting, and the nature of the data being shown) that are not in the data. This indicated that each movie by itself did not provide enough context to help visitors understand the importance of the data, and that static labels may be necessary to provide this information to visitors.

4.1.3 Design Decisions

Compared to the other two movies, the ocean currents movie tended to highlight the chemical and physical aspects rather than the biological information in the data. Without further prompting, visitors did not ask about ocean phytoplankton using the currents movie. Because of short exhibit holding times, we were concerned that some visitors might then never use the exhibit to look at marine microbes. Consequently, we decided not to start with a visualization of ocean currents.

There was no qualitative difference in interest and understandability between the two plankton movies, dominant type and plankton diversity. Nor was there a difference in the nature of questions each elicited. However, diversity seemed to be a slippery quantity for visitors; it was difficult to tell from interviews if visitors distinguished between diversity and abundance. This vagueness was not surprising, since even the idea that there are different plankton types might have been new to some visitors.

On the other hand, the dominant plankton type animation made evident the different types of plankton in the ocean. To provide visitors with the necessary background information about these plankton types, we designed a static legend shown in Figure 4 for use in the next iteration of the prototype. Since diversity can be derived from the distribution of plankton types, we decided to provide that information later in the course of exploration, instead of encoding it in the first visualization visitors would encounter.

4.2 Visualization of the Microscopic

Previous work in designing modeling and simulation tools for classrooms indicates that students often have difficulties connecting macroscopic and microscopic views of the same phenomenon [38, 36, 27]. Because Living Liquid visualizes global patterns of microscopic creatures, that are themselves likely to be unfamiliar to visitors, we decided to design coordinated visualizations that clearly link the world view to the microscopic view. The addition of a microscopic view allows for the inclusion of other types of information that are not present in the overview, such as the relative sizes of the different types of phytoplankton, and their morphological appearances, which some visitors had asked about during the previous formative evaluation.

Towards this end, we added circle viewers to our prototype visualization tool, as shown in Figure 5. The circle is intended to connote a lens, or a magnifying tool, that can be used to reveal small organisms in the ocean. In the prototype, a visitor can touch a location on the world map to open a circle viewer showing the diversity, relative size, and physical appearance of the four main types of phytoplankton defined by the Darwin Project at that location. Up to 3 circle viewers can be open at once, which we thought would be a good compromise between allowing comparisons and keeping the screen uncluttered. While a circle viewer is open, the animation of the overview movie

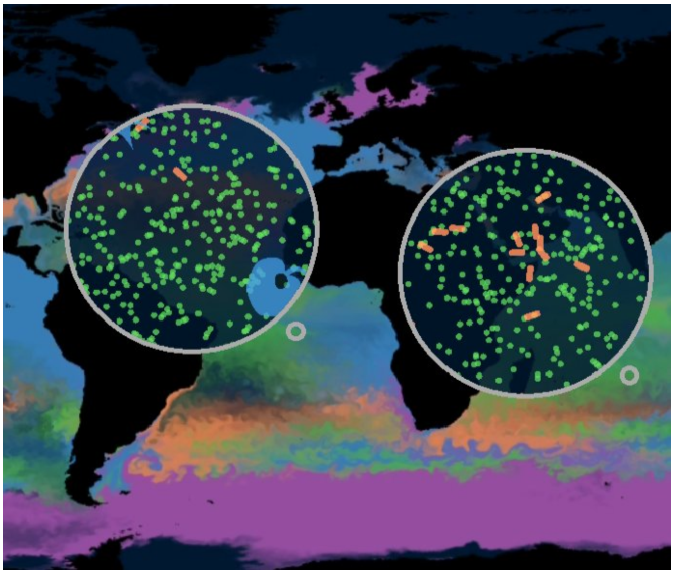


Fig. 5. Circle viewers showing the relative abundance of phytoplankton type.

is paused, allowing visitors to observe the contents of the circle without their changing, which may confuse visitors. The rest of the world map is still shown in the background, constituting a focus+context interface [5]. After 10 seconds of inactivity (no touch input), the circle viewers fade away and the overview movie resumes playback. The timeout period of 10 seconds was arrived at through subjective pilot testing; it was a compromise between the circles starting to fade out too quickly and having to wait too long for the movie to resume playback. The fade time allows users to touch the screen to keep the circle viewers open, if they wish.

Icons representing plankton populations at the selected time and place are drawn in the circle. Previous studies comparing realistic images to diagrams suggest that more realistic images are less comprehensible to novices [6, 4]. Though the question of the ideal degree of realism is still unanswered in the field, we chose to use icons representative of different plankton types, as opposed to microscope images of actual specimens, which may be foreign to visitors. Different hues are used to represent different plankton types, and the same hue is used to denote plankton of the same type in both the circle viewer and the world map.

The concentration of plankton is exaggerated within each circle viewer. A scientist looking at a drop of water collected from the ocean during a phytoplankton bloom would find perhaps one plankton instead of the number seen in the circle viewer. Instead, the number of icons drawn for each plankton type is intended to represent the relative abundance of the different types of plankton at the selected location.

In addition, the difference in scale between the larger plankton types, such as diatoms ($\approx 50\mu m$), and smaller types, such as *Prochlorococcus* ($\approx 1\mu m$), are diminished in the viewer to fit discernible icons of different types in the same circle. An accurate representation of relative size was sacrificed in favor of distinct categories of sizes, large or small. The icons for the four main phytoplankton types, the plankton concentrations to use, and the sizes of the different icons were chosen in consultation with scientists from the Center for Microbial Oceanography Research and Education (C-MORE) and the Darwin Project.

4.2.1 Formative Evaluation and Design Decision

We conducted a small formative evaluation of the circle viewer. At this point, we were primarily interested in the understandability of the visualization of the microscopic, and our evaluation focused specifically on that aspect of the prototype. Again, the purpose of this evaluation was to identify possible problems in a timely manner to inform iterative prototyping. We asked six Exploratorium visitors in the Life Sciences section to look at the prototype shown in Figure 5 and to answer a few questions. We found that five out of the six thought that the circle viewer represented the organisms found in that part of the ocean. Four also talked about abundance, while diversity was never mentioned. Visitors seemed to understand the circle viewer, so we decided to keep them in the prototype.

We also asked visitors what questions they had about what they were seeing. As in the previous evaluation, they asked questions about why certain types of plankton were found in certain areas. For example,

> *Visitor2_circle:* These [diatoms] grow in areas with lots of nutrients, but they are in the South Pole. Why?
>
> *Visitor3_circle:* It gets less and less as you get colder. Why are they living here? (Dark area in south)

This class of questions is answerable with the larger Darwin Project dataset. Because a visualization tool should allow visitors not only to ask, but also to answer their own questions, our next prototype examined ways to incorporate environmental information into the visualization.

4.3 Visualization of Environmental Conditions

The Darwin Project scientists helped select four key environmental variables to include in Living Liquid, from over 80 available in the complete Darwin Project dataset. This subset included those variables that have the largest effect on the distribution of the four types of phytoplankton shown in the visualization and those that determine the survival of one phytoplankton type versus another: nitrate, silica, and sunlight. More easily comprehensible names were given for each variable; for instance, we used "Nutrient" instead of "NO_3". Temperature was not initially included, because according to Darwin Project scientists, it was less significant than other factors in determining the locations of plankton types. However, after reviewing data from the earlier formative evaluations, we found that visitors often talked about the temperature of the ocean. We decided that showing temperature levels would answer questions that visitors may ask as they use the visualization and hoped that the more curious visitor would discern that other factors play a more critical role in plankton survival.

Representative symbols with level indicators showed the relative amount of each of the four environmental variables at selected locations. These indicators flank the circle viewer, reinforcing the circle as a view into local conditions on a global map.

To show the time of year when presenting their data, the Darwin Project scientists often use a clock-like circle, with each of the 12 months replacing the hour ticks. This approach seemed logical to us because there is an annual cycle in the distribution of environmental factors and plankton. We believed that this type of representation would allow visitors to see how fast time is passing in the exhibit, and help them realize that there are yearly cycles and seasonal variations. Thus, we implemented a similar, non-interactive time indicator in this version of the prototype, which can be seen in the supplemental video demonstration.

The prototype starts off playing a looped animation of population patterns of plankton types changing over time on a 2D world map. Visitors can touch a spot on the map, and a circle viewer appears, filled with icons representing the types and relative abundances of each type of plankton at the selected location. Each icon's hue matches the hue used to represent the population distribution of that plankton type on the world map. On the side of each circle viewer is a set of indicators showing the levels of temperature, nutrients, sunlight, and silica at the selected location, as shown in Figure 6.

4.3.1 Formative Evaluation - Method

A third evaluation was conducted to assess this version of Living Liquid with the circle viewer and indicator levels providing information, respectively, about the microscopic organisms and environmental factors for specific locations on a world map. It served to check visitors'

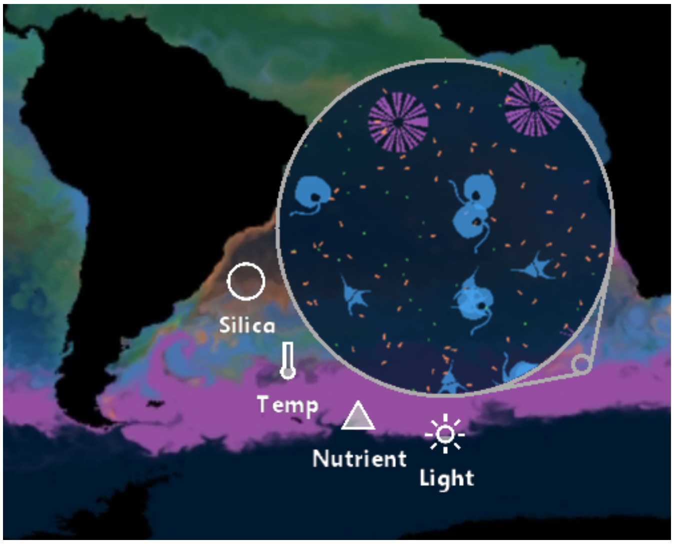


Fig. 6. Circle viewer with indicators of environmental variables at the selected location. Silica: inorganic SiO_2 concentration; Temp: temperature; Nutrient: inorganic NO_3 concentration; Light: photosynthetically available radiation.

Fig. 7. The prototype on the museum floor.

interest and the visualization's understandability given the changes to the prototype and to evaluate the visualization as a tool for exploring a richer dataset that could reveal complex relationships between plankton type, environmental factors and location. In particular, it addressed the following aspects of the visualization design:

- How interesting did visitors find the visualization? What did they find interesting and not interesting?
- How did visitors understand the visualizations used in the exhibit?
- Did the exhibit enable exploration? More specifically,
  - Did visitors look at the different types of data?
  - Did visitors see patterns and make correlations?
  - Did visitors ask and answer their own questions about the data?

Although physical robustness is an important consideration in creating any successful, maintainable exhibit, we decided to continue to focus on the visualization design before building a prototype that can withstand the sometime rough handling at a hands-on museum. Consequently, the prototype, shown in Figure 7, could not be left on the floor unattended even for a short amount of time, and evaluation depended on recruiting visitors to use the prototype with an evaluator present.

We approached every ninth group that crossed a predetermined imaginary line in the Life Sciences section of the Exploratorium and asked them to use the Living Liquid prototype for open-ended exploration and to give us feedback. Because visitors typically come in groups, and because the exhibit could comfortably accommodate only two visitors at a time, we decided to only recruit dyads — specifically, pairs in which both visitors were 11 years old or older, in keeping with the target audience for the exhibit. If both visitors were minors, we first secured permission from the accompanying adult to talk with them for the study. We asked each dyad to use the exhibit for however long they liked, in whatever ways they chose. Using a think aloud protocol, we asked each pair to talk to each other about what they saw, what they were trying to do, what they found interesting, what questions they had, and any other thoughts they had while using the exhibit. Recruiting dyads made the think aloud protocol easier to administer, since visitors were comfortable talking to their familiar partner. While visitors used the exhibit, we took copious notes, but provided no explanation or guidance. When the dyad indicated they were finished, we asked them a set of questions in a semi-structured interview. In total, we recruited 31 dyads, 20 adult pairs and 11 pairs with children, to use the exhibit for open-ended exploration.

In this evaluation, the dyad was treated as the unit of analysis, meaning that we did not distinguish one participant's response from his or her partner's. For the analysis, we categorized visitors' descriptions of what they found interesting and not interesting about the prototype. To determine how visitors understood the visualization, we looked specifically at the (mis)interpretations of the visual representation, including the color used for the different plankton type, the icons used in the circle viewer, and the environmental level indicators, in the think aloud transcripts and interview responses.

To gauge how well Living Liquid supported data exploration, we coded visitors' talk about variables represented in the visualization, looking first to see if visitors made mention of the variable, and then looked for relationships, which included patterns across location, plankton type, and environmental factors, that visitors noted. Figure 8 shows a coded excerpt from Dyad2's think aloud transcript that calls out the different types of plankton, the environmental variables, and the patterns and correlations that these two visitors noted in conversation with each other, to illustrate the application of the coding scheme. (The complete coding scheme is included with the supplemental material.) Finally, we looked through the think aloud transcripts for visitor questions that could be answered by the dataset and coded each question as having been either answered or abandoned. Twenty-three percent of the total number of think aloud transcripts were randomly selected to assess inter-rater reliability by two independent coders. Interrater reliability statistics ranged from 0.70 to 0.97, corresponding to "substantial" to "almost perfect" agreement.

4.3.2 Formative Evaluation - Results and Discussion

In the interview data, we found that visitors rated the exhibit a 4 (median) on a scale from 1 (not interesting) to 5 (interesting). They found

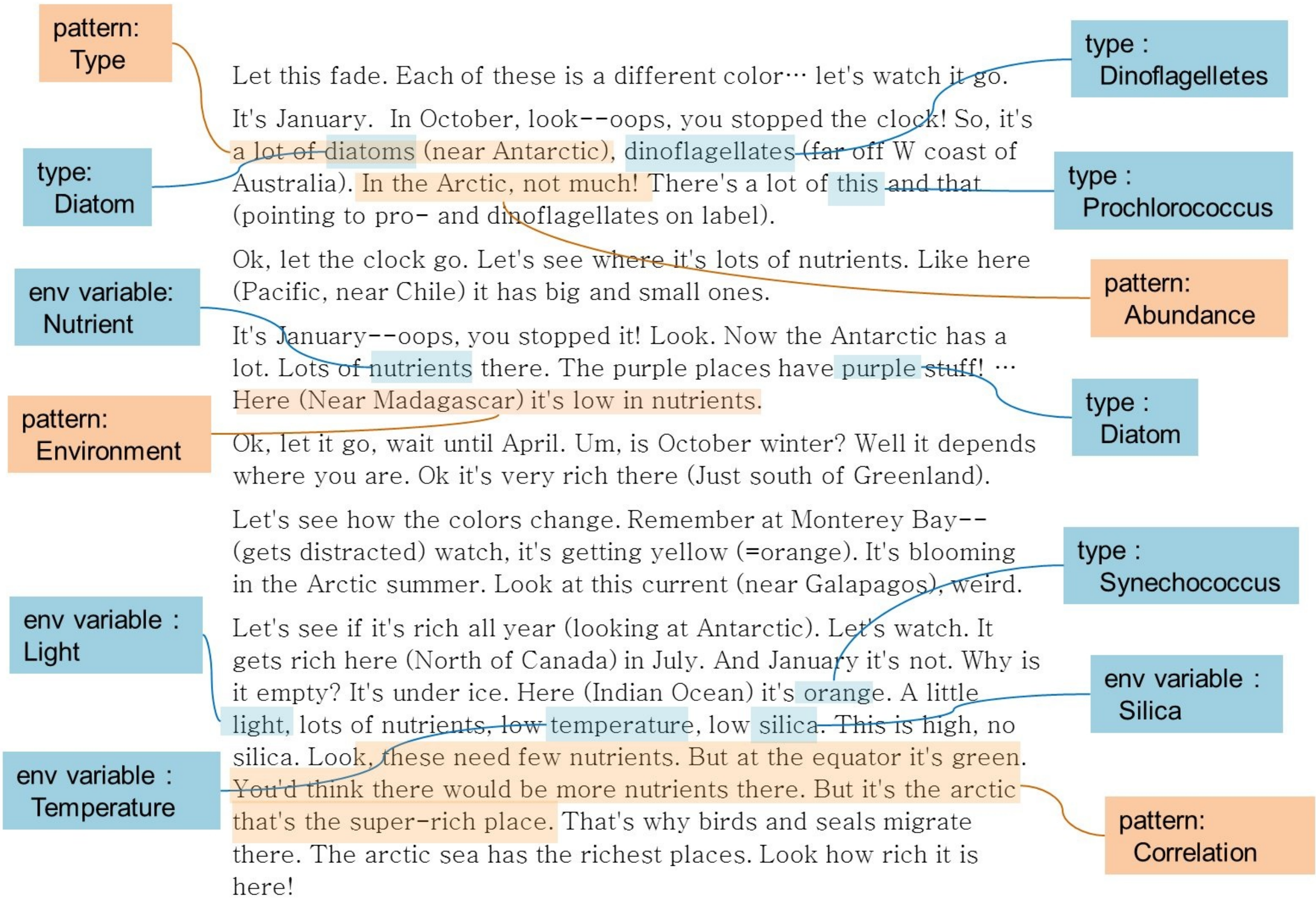


Fig. 8. Coded transcript of Dyad2's think-aloud protocol. Blue: mentions of environmental variables or plankton types; orange: mentions of patterns or correlations. Visitors asked a mean average of two data-driven questions per dyad.

Living Liquid interesting for a variety of reasons, including seeing patterns and making correlations (48%), using the touchscreen interactive (32%), learning about plankton (26%), and appreciating the aesthetics of the visuals (10%). There was no single dominant reason, which indicates that different people found different aspects of the design appealing. Alternatively, when people complained, they most often talked about the representation being difficult to understand (16%).

Looking specifically at the understandability of the visualizations, we found that 35% of visitors reported some difficulty with the visual representation during their interview. One of the key difficulties was in seeing the connection between colors used for icons in the circle viewer and colors on the world map. As one dyad explained:

> *Dyad16_E:* At first I didn't connect the colors [to the type of plankton].

When we asked specifically what the purple-pink color indicated on the map, approximately one-third did not know or incorrectly identified purple-pink as representing something other than the location of the diatoms. Looking more closely at the think aloud notes, we found that this mapping was, if not difficult, not readily evident. In the example transcript shown below, this realization comes after Dyad107 had already looked at different locations and at environmental levels.

> *Dyad107_E:* Wow, what is that? *(looking at circle viewer)* [It's] showing big bugs. That's the plankton. It shows the temperature. Can you tap on there? *(Moves to Antarctica)* Wow! Go on the pink. What do these mean? When we press on the symbol (for the environmental variables) *(Looks at label)* It shows you that this is, pink is this, this is this (maps color to plankton type).

It appears that color coding and the lens-like circle viewer as a zooming metaphor were not enough to help all visitors readily connect the microscopic and the macroscopic visualizations. Other ways of reinforcing this relationship should be explored in future work. For instance, a short zooming animation when circle viewers open, with the colors on the world map cross-fading to the view of identically-colored plankton icons, may be all that is needed to solidify this connection in visitors' minds.

From the same example, we also noticed that Dyad107 attended to a quick succession of different parameters in the visualization, starting from the map, to the circle viewer and its icons, to the environmental factors, to the map again, and then specifically to the colors on the map. We wonder if the number of variables, including four different plankton types and four different environmental factors, in combination with the time-lapse overview animation and the zoomed circle interface, made it difficult to comprehend and synthesize the visualization as a whole.

On average, in the analysis of their think aloud protocols, we found that visitors remarked on 3 (median) out of the four different plankton types and 3 (median) out of the four different environmental factors.

Almost all visitors talked about at least one type of plankton (97%) and at least one kind of environmental variable (87%). Furthermore, 97% talked about seeing some kind of pattern: where a certain type of plankton could be found, if there were a lot or a few at a location, or the environmental levels at different areas of the ocean. These results suggest that visitors used the visualization tool to look at different aspects of the Darwin Project dataset and that visitors noted geographic patterns.

However, the more complex relationships were less evident; a smaller number (52%) of visitors correlated the type of plankton found at a location with the environmental conditions at that location. This adds support to the conjecture that there may be too many variables immediately available in the visualization for visitors to readily understand.

Alternatively, when we coded the think aloud transcripts for questions that visitors generated that were answerable with the given dataset, we found on average, visitors asked two data-driven questions, and a majority of visitors answered the questions they asked using the exhibit to find the information they needed.

These results indicate that visitors were able to use Living Liquid to explore the dataset, asking and answering their own questions. However, the visualization could be improved for understandability, and further iterations would need to determine how to layer access to the richness of the scientific dataset to better guide inquiry.

5 Lessons Learned

The main lessons learned during our iterative prototyping design process include the following:

5.1 Prioritize data you want visitors to explore

The first thing visitors see in an interactive visualization should prioritize the content or skills they should walk away with. Avoid using an "opening act" that, while attention-grabbing, has the potential to derail visitors from asking questions about the rest of the dataset. On the other hand, remember that visitors may simply walk away without exploring the data if they don't find the initial visualization engaging enough. This lesson was highlighted most clearly by the use of a currents visualization to engage people with plankton patterns. Visitors were so mesmerized and interested in global ocean currents that it was difficult to engage them with data about plankton.

If dealing with a complex, multivariate dataset, prioritize the data to visualize. Visitors have limited time, limited interest, and limited expertise, which means that they may be unable or unwilling to explore every aspect of a scientific dataset. Selection should take into account what visitors are familiar with and what visitors are interested in. Evaluation with visitors before and during exhibit development can help identify their range of familiarity and interests.

5.2 Incorporate background information into the visualization

Visitors come to a visualization with varying levels of prior knowledge about the scientific content and research. When possible include any information that may help the visitor interpret the visualization. So, if the visualization shows data about the diversity and abundance of microscopic organisms, provide complementary visualizations that describe these organisms. However, special care needs to be taken to link these complementary visualizations. For example, interfaces, such as focus+context, may be effective for experts, but visitors may require additional reinforcement to associate a variable displayed at one scale with the same variable displayed at a different scale. Color-coding and a select-to-zoom metaphor may not be enough.

5.3 Favor understanding of key concepts over scientific accuracy

Throughout our design process, we had to make difficult decisions about the level of scientific accuracy the visualization should represent. In many cases, scientific accuracy interfered with the understandability of the visualization. Previous sections of this paper described our decision to diminish the size difference between the smallest and the largest plankton types and to exaggerate the concentration of plankton represented in the circle viewers. As another example, there are always many orders of magnitude more of the small bacteria plankton type, *Prochlorococcus*, than the larger diatoms. If the team produced a visualization that was scientifically accurate, visitors would only ever see the *Prochlorococcus* and not the diatoms, making it seem as though the sea were swimming with tiny bacteria and nothing else. With our scientific advisors, we decided to emphasize relative amounts as the key concept, and the visualization was scaled accordingly.

5.4 Layer the accessibility of different types of data

Open-ended exploration can be difficult for novices, who can quickly become overwhelmed with a plethora of data types and representations. Visitors need guidance in how to ask and answer questions with data, and providing layered access to the information is one way of structuring visitor inquiry. This allows visitors to focus on simpler relationships (e.g, there are different types of plankton in the ocean) before exploring more complex correlations (e.g., where the different types live depends on a set of interacting environmental factors). In the next iteration of the prototype, we will experiment with displaying only plankton types within circle viewers, and only showing environmental factors after visitors open an information screen attached to a viewer.

6 Conclusion

The work documented here represents a case study of the iterative design and development of a visualization exhibit that gives museum-goers the opportunity to explore, and thereby engage with, scientific datasets generated by, and used in, active research. It represents the beginning of a larger effort to identify and address challenges in creating visualization tools for exploring large scientific datasets in museums. This paper focused on the challenges in designing visualization tools that can engage visitors' interests, that are readily understandable, and that allow visitors to participate in data exploration by asking and answering their own questions about the dataset.

Future work includes greater consideration of the social interactions that arise when using a visualization tool. For instance, visualizations can incorporate large, dynamic interfaces to accommodate visiting groups. Prior work by Hinrichs [20, 19] have identified the importance of fostering collaboration to promote productive data exploration within these groups, but additional work is needed to develop successful examples and to better identify what allows fruitful social interactions with data visualizations.

In addition to being social environments, many science museums are physically interactive spaces that provide visitors with hands-on opportunities. Tangible interfaces can extend visualization tools into the physical realm, but bring their own promises and pitfalls. With the next iteration of Living Liquid, we hope to address the challenge of designing for the social and physical dimensions of the museum context.

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