Using Digital Globes to Explore the Deep Sea and Advance Public Literacy in Earth System Science

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ABSTRACT

Digital globes are new technologies increasingly used in informal and formal education to display global datasets and show connections among Earth systems. But how effective are digital globes in advancing public literacy in Earth system science? We addressed this question by developing new content for digital globes with the intent to educate and excite the public about biological and geophysical processes and exploration in the deep ocean. We developed the content in tight collaboration with scientists, educators, and graphic artists. We used global datasets, including a new dataset for locations of deep-sea vents, and imagery from deep-diving vehicles to create two narratives, Life Without Sunlight and Smoke and Fire Underwater, each targeting a set of Earth Science and ocean literacy principles. Here, we evaluate perceived learning outcomes for the narratives delivered as movies and as live, docent-led presentations with the room-sized Science On a Sphere®. Both narratives led to median responses of "Some" to "Quite a bit" of perceived learning per literacy principle. Perceived learning outcomes were greatest for adult lifelong learners, followed closely by students (under age 18); adult educators generally reported less learning. We found no significant differences in the effectiveness of our movies compared to docent-led presentations for any of the literacy principles, and all presentations led to "Quite a bit" of excitement for all viewers. Our evaluation provides an initial indication that digital globes can be effective in teaching the scientific literacy principles, and we make recommendations for additional assessment of digital globes as educational platforms. © *2015 National Association of Geoscience Teachers*. [DOI: 10.5408/14-067.1]

Key words: hydrothermal vent, ocean literacy principles, Earth Science literacy principles, Science On a Sphere

INTRODUCTION

Spherical display systems, also known as digital globes, are new technologies that can inspire students and public audiences to learn about Earth system processes. A review of research on data visualization experiences including digital globes indicated "a variety of positive impacts on learning" (Goldman et al., 2010). Digital globes can be used to display a growing variety of global datasets—from near-real-time earthquakes in the context of Earth's plate boundaries, to changes in primary productivity over seasonal cycles on land and in the ocean, to hurricane tracks, animal migrations, and more. Digital globes also are growing in popularity as unique platforms on which to screen films (e.g., Starobin, 2006). It is likely not just the display of datasets in a global context but also the construction of science stories, navigating the datasets, that leads to new learning (Klassen, 2009). For example, the importance of narrative accompanying geospatial visualization has been recognized for public literacy in climate science (Niepold et al., 2008; Schollaert Uz et al., 2014).

We were interested in using digital globes to advance public literacy in Earth system science—linking the lithosphere, hydrosphere, atmosphere, and biosphere. In particular, we were interested in developing content for informal educational settings that would target ocean literacy principles (OLPs; Ocean Literacy, 2005; Strang et al., 2007; Schubel et al., 2009). Studies of public ocean literacy often focus on the coastal marine environment (e.g., Steel et al., 2005), but we were interested in public knowledge about the deep ocean and connections to the deep Earth. Public audiences have been captivated by imagery of deep-sea hydrothermal vents, also known as hot springs at the seafloor, including seafloor eruptions and unique ecosystems thriving in an otherwise cold, dark ocean. Can we connect such imagery with global datasets to enable people to understand the global context and significance of vents in the world ocean and in the dynamic processes of Earth?

We developed a partnership between the Woods Hole Oceanographic Institution and the Ocean Explorium in New Bedford, MA, to create content for spherical display systems, including Science On a Sphere® (SOS). SOS is a room-sized (1.7-m-diameter) digital globe that was developed by the National Oceanic and Atmospheric Administration (NOAA) for visualization of global datasets "as if the viewer were looking at the Earth from outer space" (Albers et al., 2005). NOAA's online SOS Data Catalog includes almost 500 datasets categorized to air, land, water, space and more (NOAA, 2015). As of fall 2014, the Ocean Explorium was one of more than 100 science museums in 20 countries around the world that host an SOS (Kramer, 2014). We created datasets for SOS, including locations of Earth's known deep-sea hydrothermal vents from the InterRidge Vents Database (Beaulieu et al., 2013), and six site-specific movies for vents visited by deep-sea vehicles. Our project was called the Global Viewport to Deep-Sea Vents in honor

Received 24 November 2014; revised 6 August 2015; accepted 2 September 2015; published online 14 December 2015.

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of the launching of the new human-occupied vehicle Alvin in 2014, with its improved viewports for scientific observations.

We linked our new datasets with other datasets from the SOS Data Catalog to create science stories with the intent to educate and excite the public about biological and geophysical processes and exploration in the deep ocean. Ultimately, we developed two educational narratives, Life Without Sunlight (LWS) and Smoke and Fire Underwater (SFU)—each focusing on a different set of OLPs (Ocean Literacy, 2005) and Earth Science literacy principles (ESLPs; Wysession et al., 2010, 2012). We delivered the two narratives to public audiences using the SOS at the Ocean Explorium as two types of presentations: either as a movie or as a live, docent-led, interactive presentation. The live, docent-led presentations used the same datasets and additional site-specific video imagery, expanding on the script of the narrated compilation movies. Later, we describe how we evaluated the effectiveness of the two narratives and two types of presentations with respect to the targeted scientific literacy principles and level of engagement of the audience. Our study is one of the first to examine the effectiveness of a narrated movie as a stand-alone presentation on the SOS.

We were also interested in knowing whether our new content for the SOS was as effective for students as for adults. The SOS cross-site summative evaluation study was mainly designed for adults over age 18 (Goldman et al., 2010); thus, our data would fill a gap in understanding how public audiences of all ages experience the SOS. In a report prepared for the NOAA Education Program, Tran (2009) noted challenges for public understanding of complex systems, especially evident for "students and novices" compared to "professionals and scientists." In particular, students "tend to miss the interconnectedness and complex causal relationships within and among systems" (p. 25 in Tran, 2009). The National Academies' Committee on Learning Science in Informal Environments noted that programs may need to be tailored to age groups, distinguishing "children and youth" from "adults, including K–12 teachers" (Bell et al., 2009). In our study, we distinguished students (under age 18), adult lifelong learners, and adult educators to address these differences and to fulfill goals of the U.S. National Science Foundation, including "preparing the geoscience workforce of the future," "life-long learning in… informal educational settings," and educators' use of "the big ideas" in ocean literacy and Earth Science literacy frameworks (p. 10–11 in National Science Foundation Advisory Committee for Geosciences, 2012).

DATASETS AND TWO STORIES FOR SOS

We conducted a front-end evaluation at our respective institutions and at the 2012 SOS Users Workshop to gauge public knowledge of deep-sea vents and to aid our choice of literacy principles. In particular, we focused on concepts recognized as important for public literacy of Earth system science: productivity inclusive of marine photosynthesis and chemosynthesis, biodiversity inclusive of marine ecosystems, geography inclusive of seafloor bathymetry, and plate tectonics inclusive of seafloor spreading (Strang et al., 2007). For example, previous studies indicated that undergraduate students, even when enrolled in Earth Science courses, lack understanding of volcanic systems and plate tectonics (Parham et al., 2010). We identified a subset of OLPs (Ocean Literacy, 2005) and ESLPs (Wysession et al., 2010) to target specifically as we developed our new content.

We developed our new content through a process similar to an iterative software development process (Fox and McGuinness, 2008) in which our use case was to develop an educational package for spherical display systems that would highlight deep-sea vents while linking concepts to advance public literacy in Earth system science. The use case process is essentially a cycle in which a prototype is rapidly developed and evaluated (through formative evaluation) with respect to specific goals. Our design process involved tight collaboration in a small team with diverse skills, including a lead scientist, educators at both institutions, graphic artists, and a professional evaluator. To scope the data and related resources available for our project, we started by assessing the available high-definition imagery from deep-sea vehicles, georeferenced the imagery to locations of hydrothermal vent fields in the InterRidge Vents Database (Beaulieu et al., 2013), and determined other datasets in the SOS Data Catalog that were relevant to our goals. The design specifications for our science stories linking the datasets had to take into account the limited time for museum visitors, their potential lack of background knowledge to interpret data visualizations, and visual impact (e.g., Ma et al., 2012a). Similar to work in the film industry, we used storyboarding to aid the development of our compilation movies, which include datasets and other geoanimations, additional video imagery, and sound (Starobin, 2006; Riedl and Wintner, 2013). For docent-led presentations we adopted new features (e.g., layering and annotation) in SOS Version 4. The collaboration entailed three iterations of the use case cycle in which the latest prototype was evaluated in person by the project team at the SOS at the Ocean Explorium. Collaborating in a small team with mixed skills, each had a role to guide the prototype toward a specific goal (e.g., scientist for choosing datasets, educators for teaching literacy principles, graphic artists for visual impact, and an evaluator to guide our formative evaluation).

Our final product is an educational package that includes datasets, movies, scripts, and playlists that incorporate other SOS datasets. Our datasets include a static and an animated version of the InterRidge Vents Database showing the discoveries of deep-sea vents through time since 1977. Movies include six site-specific movies for deep-sea vents (Axial Seamount, Galapagos Rift, Loihi, Mariana Back-Arc, Mid-Cayman Rise, and Mata volcanoes) and two narrated compilation movies that interweave global datasets with selected portions of the site-specific movies. The full package is available for download at the Woods Hole Open Access Server (Beaulieu et al., 2014), and educational compilation movies were rendered for posting on YouTube (Woods Hole Oceanographic Institution, 2014). The datasets and movies formatted specifically for the SOS are available from the NOAA SOS Data Catalog (NOAA, 2015).

Ultimately, we constructed two narratives, each highlighting three deep-sea vents, and each targeting a different set of three literacy principles (Fig. 1). Our two narratives, LWS and SFU, were produced as the two compilation movies, with content and scripts matched to live, interactive, docent-led presentations. We aimed for less than 5 min per movie, given previous research indicating the amount of

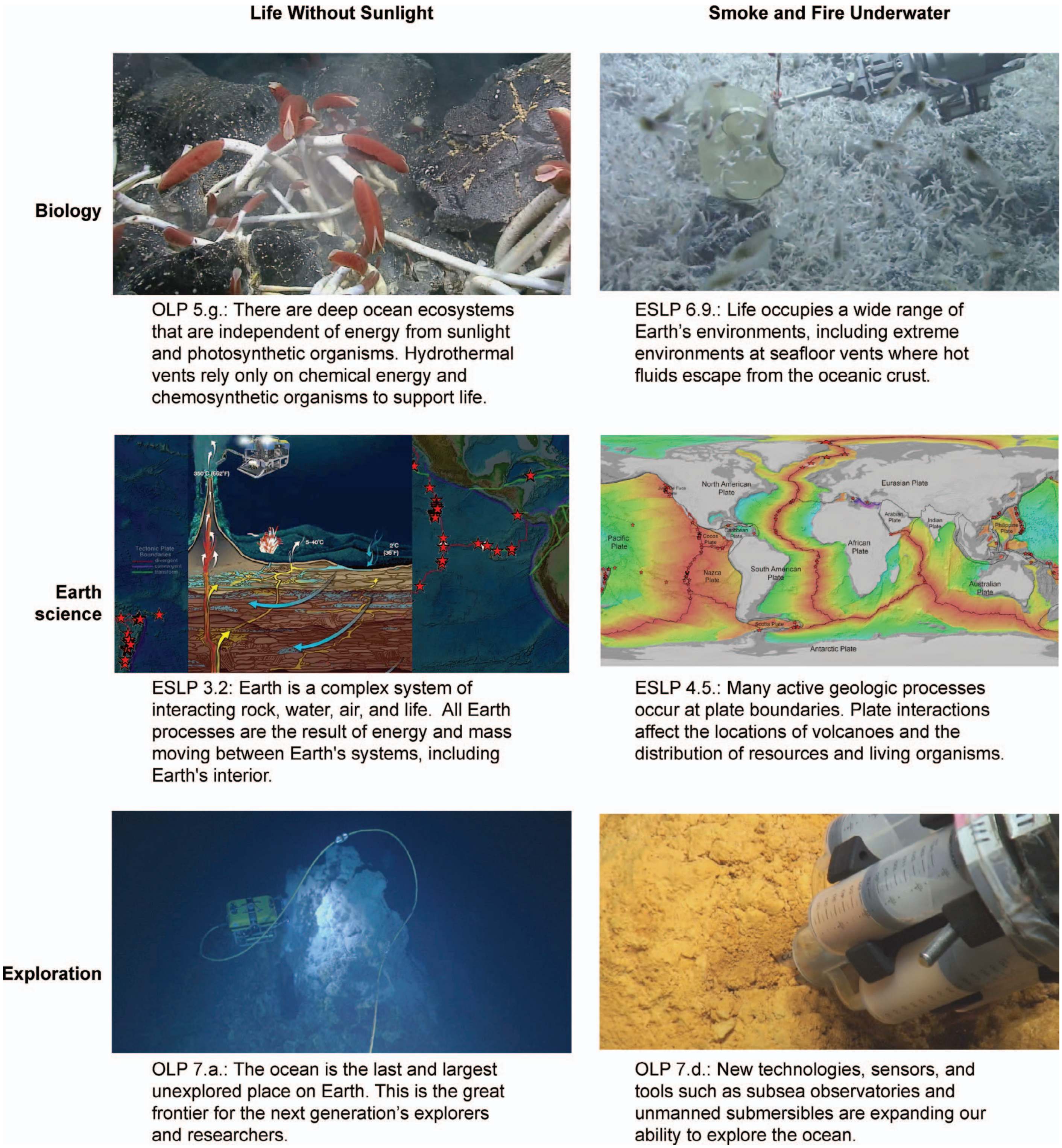

FIGURE 1: Screen grabs from our two narratives and targeted OLPs or ESLPs verbatim from our survey instrument. (Color for this figure can be found in the online version of this paper.)

time that the public interacts with stand-alone SOS exhibits (Mitchell et al., 2012), and about 20 min for a docent-led presentation. The docent-led presentations allow more time to play each site-specific movie in full and to interact with the audience. LWS dives beneath the sunlit ocean to the darkness of deep-sea vents, where food webs are fueled by chemosynthesis, and specifically targets OLP 5.g: "There are deep ocean ecosystems that are independent of energy from sunlight and photosynthetic organisms." In addition, LWS targets ESLP Big Idea 3: "Earth is a complex system of interacting rock, water, air, and life," previously identified by geoscience educators as an important integrated concept for Earth system science literacy (Ladue and Clark, 2012). SFU asks whether the viewer knows that there are volcanoes in

TABLE I: Residence of survey participants.

City or Town	Students	Lifelong Learners	Educators
New Bedford	29%	40%	28%
Fall River	17%	5%	9%
Town on Cape Cod	10%	5%	23%
Other town in southeastern Massachusetts	35%	40%	30%
Outside of southeastern Massachusetts	8%	12%	9%

the deep sea with vents spewing hot water and specifically targets ESLP 4.5: "Many active geologic processes occur at plate boundaries." Both educational narratives integrate a number of other datasets available for the SOS, including bathymetry, Volcano Locations Globally, and Age of the Seafloor.

We use the term "narrative" to clarify that our two "stories" were constructed carefully with the intent for the audience to learn from and be engaged with the materials. Our definition of narrative is relatively aligned with p. 539 in Norris et al. (2005), in that we have a "sequence of events about a unified subject...connected so that individual events can be seen in the perspective of others"; however, our sequence of events is more in space than in time (although LWS starts with the first discovery of deep-sea vents). We do not employ characters in our stories, per se; however, Norris et al. (2005) point to a more general definition of characters that includes entities, which in our case are the deep-sea vents highlighted in each story. We also considered other elements of narratives as outlined by Norris et al. (2005) with the addition of "The effect of the untold" (p. 402 in Klassen, 2009), important because of the limited amount of time to provide a sphere story.

METHODS FOR SUMMATIVE EVALUATION

For our summative evaluation of the two narratives for the SOS, we focused on two impact categories for informal science education: (1) "Awareness, knowledge or understanding (of)" and (2) "Engagement or interest (in)" (p. 11 in Friedman, 2008). For learning outcomes, we targeted the three scientific literacy principles per narrative (Fig. 1), categorized later as the biology, Earth Science, and exploration principles. For engagement, we chose the concept "excited" from the positive and negative affect schedule (Watson et al., 1988).

We conducted a posttest-only experimental design with self-reporting of knowledge gained and level of engagement. Our choice of assessment via perceived learning was in part because of our posttest-only design. Our survey instrument consisted of a questionnaire with seven questions: three demographic, three related to literacy principles, and one related to engagement, plus an additional question for professional educators (Supp. File 1, which can be found online at http://dx.doi.org/10.5408/14-067s2). To reduce the time needed to complete the survey (and increase the likelihood of participation in it), we limited the number of questions on the survey instrument. To reduce the amount of text in the survey instrument, we used a subset of the words in each literacy principle (we paraphrased one principle, ESLP 3.2). The survey instrument was refined by testing with staff at the Ocean Explorium to improve clarity and ensure the time to complete the survey was less than 5 min. The survey was provided either online using eSurveysPro software (Outside Software, Inc.) or as a paper hard copy. For the online surveys, we installed a kiosk outside the entrance to the SOS auditorium, and we provided several iPads on site and posted a quick response code for participants to use their smart phones to complete the survey after the presentation. All surveys were anonymous.

Demographic questions were mandatory; the first had three options as categories only to determine whether the respondent was a student (under 18 years of age) or adult (age 18 or older), with adults selecting "lifelong learner" or "educator." The second demographic question determined where the respondent lived (categories in Table I). Particularly for the students, another goal of this project was to engage underrepresented students from schools in the Massachusetts South Coast region, which includes the cities of New Bedford, Fall River, and 12 surrounding towns. We used the answer to the residence question as a proxy for underrepresented populations. For example, New Bedford has a diverse population, with greater proportion of "Hispanic or Latino," "American Indian," and "Two or more races" than average in Massachusetts (2010 data from U.S. Census Bureau, 2014). In New Bedford, 37% of the residents speak a language other than English at home (2008–2012 data from U.S. Census Bureau, 2014). In 2013–2014, 76% of the students in public schools in New Bedford and 78% in Fall River were classified as low income compared to 38% for the state (Massachusetts Department of Elementary and Secondary Education, 2014). Although census geography may serve as a proxy for race or ethnicity, we recognize that it is not as strong a predictor as when combined with additional data (e.g., Elliot et al., 2009); however, this single question also satisfied the museum's interest in where its visitors were coming from. The third demographic question determined the respondent's level of educational attainment (categories in Table II). High school graduation rates of 59% for New Bedford and 73% for Fall River are low compared to the state rate of 85% (2013 data; Massachusetts Department of Elementary and Secondary Education, 2014). The proportion of the population in New Bedford with a bachelor's (or higher) degree is just 15%, less than half the average in Massachusetts (age 25+ 2008–2012 data from U.S. Census Bureau, 2014).

For self-reporting of knowledge gained, i.e., perceived learning outcomes, we used the same structure for each question: We wrote out the literacy principle (listed in Fig. 1), asked respondents to indicate whether "as a result of seeing today's presentation, my knowledge of the above subject has increased," and then provided a four-category Likert scale for a single response: "Not at all," "A little," "Some," or "Quite a bit." These survey questions are more specific than

TABLE II: Educational attainment of survey participants.

	Students	Lifelong Learners	Educators
Not yet completed high school	98%	7%	0%
High school graduate or GED	2%	9%	5%
Some college, no degree		12%	7%
Associate's degree		16%	5%
Bachelor's degree		35%	26%
Graduate/advanced degree		21%	58%

the "Did you learn anything new"? (yes/no) in the study by Goldman et al. (2010), because we were targeting perceived learning of specific literacy principles. We provided the same four-category scale for the engagement question, "After today's presentation, how excited are you about the great unexplored deep ocean frontier and the exploration and research of deep-sea vents"? Educators received an additional question for the likelihood of using what they learned in their educational activities (four-category scale from "Definitely won't" to "Definitely will").

To attract participation in the survey, we hosted three events for the public, including two free family science nights at the Ocean Explorium, highlighting the LWS or the SFU narrative. One reason for holding events at no cost was to attract visitors of lower socioeconomic status to the museum; previous research has indicated that lower socioeconomic status correlates to lower knowledge of environmental and ocean sciences (e.g., Steel et al., 2005). We also highlighted the new content during school field trips and a teacher professional development workshop at the Ocean Explorium. For the workshop, we focused on attracting teachers from schools in the Massachusetts South Coast region. Of the total of 158 survey responses received, 135, or 85%, included data for self-reporting of knowledge gained and level of engagement. Although we attracted many visitors to the museum during the two free events and we offered incentives to those filling out the surveys, it was challenging to obtain completed surveys (e.g., 18 completed surveys for 160 visitors, or 11%, at the second free event).

To assess perceived learning outcomes and excitement generated by viewing the presentations, we examined descriptive statistics (i.e., histogram, mode, and median of responses) and conducted nonparametric statistical tests appropriate for the categorical data, assigning the progressive positive integer values 1 through 4 to our four-level Likert scale. We did not infer the distance between each successive item category to be equivalent and thus only performed tests with ranks. Within each group (students, lifelong learners, and educators), we tested the effectiveness of the movie vs. the docent-led presentation using a Wilcoxan rank sum test, and we tested for differences among the groups for each type of presentation using a Kruskal-Wallis test (e.g., Hollingsworth et al., 2011). Our numbers of responses led to an unbalanced design (Supp. File 2, which can be found online at http://dx.doi.org/10.5408/14-067s1), precluding a Friedman test as a nonparametric two-way analysis of variance. All statistical tests were performed with Matlab software R2010b (The MathWorks, Inc).

STUDY DEMOGRAPHICS

Our total of 135 participants included 48 students and 87 adults (43 lifelong learners and 44 educators). For the students, most (81%) resided in the Massachusetts South Coast region (New Bedford 29%, Fall River 17%, and 12 surrounding towns 35%; Table I). For the level of educational attainment, almost all students selected "Not yet completed high school" (Table II). Half of the students were exposed to either narrative, and for each narrative approximately half saw the movie while the other half saw the docent-led presentation (see Supp. File 2 for maximum number of respondents to each survey question).

A similar majority (85%) of the adult lifelong learners came from the Massachusetts South Coast region (New Bedford 40%, Fall River 5%, and other South Coast towns 40%; Table I). Their levels of educational attainment represented all six categories, including "Not yet completed high school" (7%; Table II); however, the percentage with bachelor's degrees (35%) was greater than expected for the South Coast region and more aligned with the state of Massachusetts. Half of the lifelong learners were exposed to either narrative, and for each narrative approximately half saw the movie while the other half saw the docent-led presentation (see Supp. File 2 for maximum number of respondents to each survey question).

For the adult educators who participated in the survey, 67% were from the Massachusetts South Coast region (New Bedford 28%, Fall River 9%, and other South Coast towns 30%; Table I). Their level of educational attainment exceeded the lifelong learners, with more than half (58%) of the educators having graduate degrees (Table II). More educators saw the LWS narrative; our sample size was least for the educators who saw the docent-led presentation of SFU (Supp. File 2).

RESULTS FOR ASSESSMENT OF LEARNING AND ENGAGEMENT

For all combined survey respondents, both the LWS and the SFU narratives led to median responses of "Some" to "Quite a bit" of perceived learning per literacy principle (Table III). Comparing the two narratives for all combined respondents, self-reported knowledge gains ranged from 91% to 94% per literacy principle (inclusive of the "A little," "Some," and "Quite a bit" categories) for LWS and 94% to 98% for SFU (Supp. File 2). Comparing descriptive statistics (histograms, modes, and medians) between the two narratives, LWS (Fig. 2) led to greater perceived learning for the biology principle, while SFU (Fig. 3) led to greater perceived learning for the Earth Science principle (Table III, Supp. File

TABLE III: Medians of survey responses. "Quite a bit" responses are in bold.

Narrative and Literacy Principle	Students		Lifelong Learners		Educators		Total Combined	
	Movie	Docent	Movie	Docent	Movie	Docent	Movie	Docent
LWS								
Biology	**Quite a bit**	**Quite a bit**	**Quite a bit**	**Quite a bit**	Some	Some	**Quite a bit**	**Quite a bit**
Earth Science	Between some and quite a bit	Some	Between some and quite a bit	Some	Some	Some	Some	Some
Exploration	**Quite a bit**	A little	**Quite a bit**	Some	Some	Some	Between some and quite a bit	Some
Excitement	**Quite a bit**	**Quite a bit**	**Quite a bit**	**Quite a bit**	**Quite a bit**	**Quite a bit**	**Quite a bit**	**Quite a bit**
SFU								
Biology	Some	Some	Some	**Quite a bit**	Some	Some	Some	Some
Earth Science	Some	Between some and quite a bit	Between some and quite a bit	**Quite a bit**	Some	**Quite a bit**	Some	**Quite a bit**
Exploration	Some	Between some and quite a bit	Some	Between some and quite a bit	Between some and quite a bit	Between a little and some	Some	Some
Excitement	**Quite a bit**	**Quite a bit**	**Quite a bit**	**Quite a bit**	**Quite a bit**	**Quite a bit**	**Quite a bit**	**Quite a bit**

2). Both narratives were equally effective in generating "Quite a bit" of excitement (Fig. 4 and Table III). Results of the Wilcoxan rank sum tests indicated no significant differences between the type of presentation (movie vs. docent led) for the respondents grouped as students, lifelong learners, or educators (Supp. File 2). Results of the Kruskal-Wallis tests also indicated no significant differences among students, lifelong learners, and educators for either of the movies or the docent-led presentations (Supp. File 2). However, some interesting patterns for learning outcomes are apparent when comparing the descriptive statistics within and among the groups of respondents, which we highlight below.

Assessment of Students

Based on median responses, students appeared to learn more from LWS than from SFU (Table III), although this distinction was not apparent based on modes or combined percentages of self-reported new learning per literacy principle (Supp. File 2). For LWS, histograms for student learning outcomes were well matched between the two types of presentations [Figs. 2(a), 2(d), and 2(g)], especially for the biology and Earth Science principles. For the exploration principle, students were split between reporting either "A little" or "Quite a bit" of knowledge gained, with greater median response for the movie [Fig. 2(g) and Table III]. For SFU, histograms for student learning outcomes also appeared well matched between types of presentation [Figs. 3(a), 3(d), and 3(g)], although the median responses suggest more perceived learning from the docent-led presentation for the Earth Science and exploration principles (Table III). In terms of excitement about the great unexplored deep ocean frontier, students responded more to the docent-led presentation of LWS [Fig. 4(a)], but their response was most dramatic (100% "Quite a bit") to the movie of SFU [Fig. 4(d)].

Assessment of Lifelong Learners

In general, lifelong learners reported similar to slightly more knowledge gains than students for both narratives (Table III, Supp. File 2). Based on median and mode responses, neither narrative appeared more effective overall for lifelong learners; however, for LWS, 100% of the lifelong learners reported at least "A little" new learning for all three literacy principles for both types of presentations [Figs. 2(b), 2(e), and 2(h)]. For LWS, histograms for learning outcomes for lifelong learners were not well matched for the Earth Science and exploration principles, with the movie appearing more effective than the docent-led presentation [Figs. 2(e) and 2(h)]. For SFU, lifelong learners had greater response to the docent-led presentation for all three literacy principles [Figs. 3(b), 3(e), and 3(h) and Table III]. In contrast to the students, for level of engagement, the lifelong learners responded more to the movie of LWS [Fig. 4(b)], but most dramatically (100% "Quite a bit") to the docent-led presentation of SFU [Fig. 4(e)].

Assessment of Educators

In general, responses to literacy principles indicated that educators perceived less learning than lifelong learners for both narratives (Table III, Supp. File 2), and this was particularly evident for LWS (Fig. 2). Overall, educators

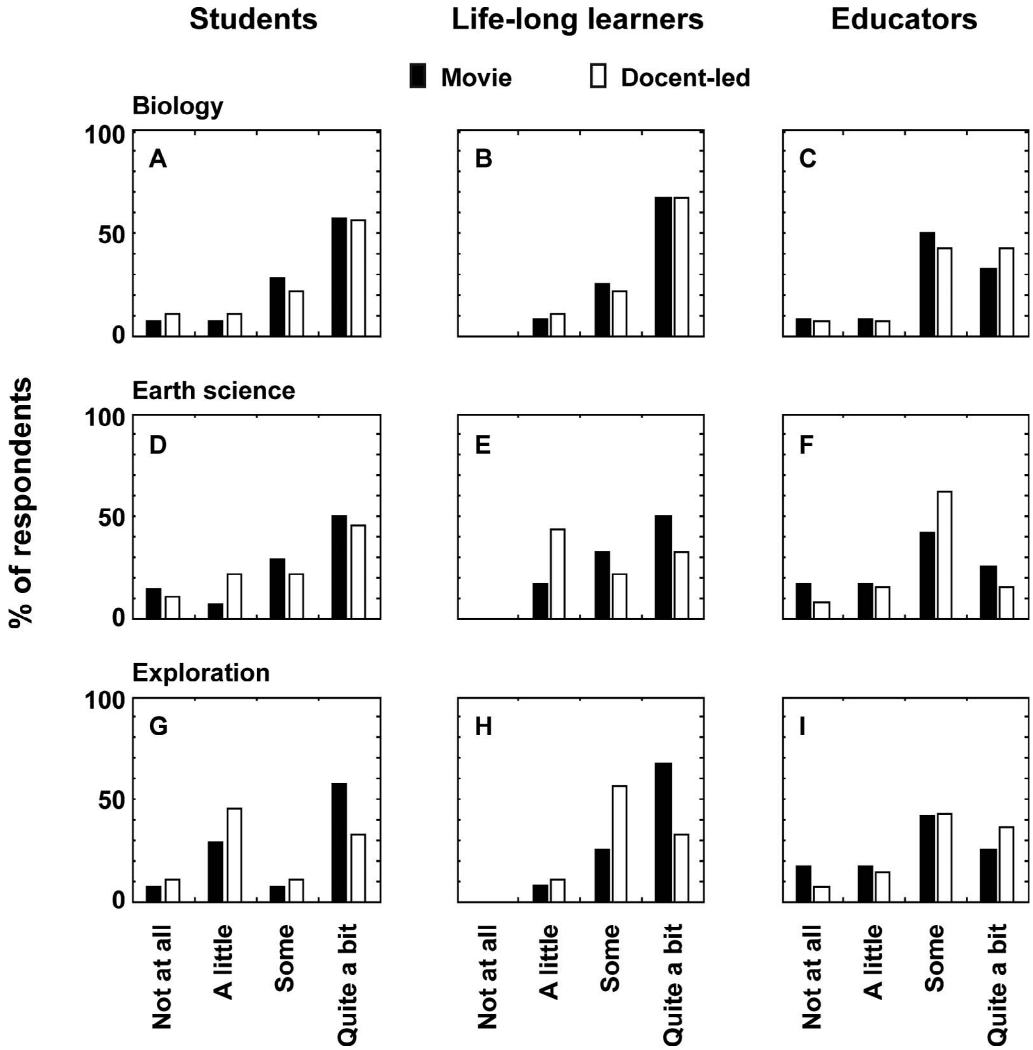

FIGURE 2: LWS narrative, perceived learning outcomes for three scientific literacy principles: upper (a–c), biology; middle (d–f), Earth Science; lower (g–i), exploration. Y-axis = percentage of respondents. (Left) Students (number of respondents, $n = 14$ movie, 9 docent-led); (center) lifelong learners ($n = 12$ movie, 9 docent-led), and (right) educators [$n = 12$ movie, 14 docent-led, with the exception of 13 docent-led in (f)].

appeared to learn more from SFU (Table III, Supp. File 2). For LWS, histograms for educator learning outcomes were well matched between the two types of presentations [Figs. 2(c), 2(f), and 2(i)], which was not the case for SFU [Figs. 3(c), 3(f), and 3(i)]. Educators responded more to the docent-led presentation of SFU for the biology and Earth Science principles, which was similar to the lifelong learners, but more to the movie for the exploration principle, in contrast to lifelong learners (Fig. 3, Supp. File 2). Educators were not as excited as students or lifelong learners by either presentation of LWS [Fig. 4(c)]. However, the SFU movie led to the most dramatic (100% "Quite a bit") excitement for educators [Fig. 4(f)], matching the students. Combining responses to both narratives and both types of presentation, most educators reported that they probably or definitely would incorporate their new learning into their classrooms (92% combined responses; Fig. 5). In particular, for the docent-led presentation of SFU, 100% of the educators reported that they definitely would incorporate their new learning in the classroom [Fig. 5(b)].

DISCUSSION

Digital Globes Effective in Teaching OLPs and ESLPs

Our survey results support a key finding from the cross-site summative evaluation of SOS as a platform for informal education—that visitors report new learning from SOS presentations (Goldman et al., 2010). Our survey results demonstrate more specifically that students and adults perceived an increase in their knowledge of ESLPs and OLPs presented through our new content developed for SOS. Our results for self-reported knowledge gains ranged from 91% to 98% per literacy principle for all combined respondents, compared to 71% of visitors reporting new learning in the SOS cross-site summative evaluation (Goldman et al., 2010). In general, perceived learning outcomes in our study appeared greatest for the adult lifelong learners, followed closely by students; adult educators generally reported less learning, as expected with their higher level of educational background. Also not surprising was our finding that each narrative led to greater learning for the particular disciplinary principle reflected in its respective title. Our attempts to increase the participation of under-

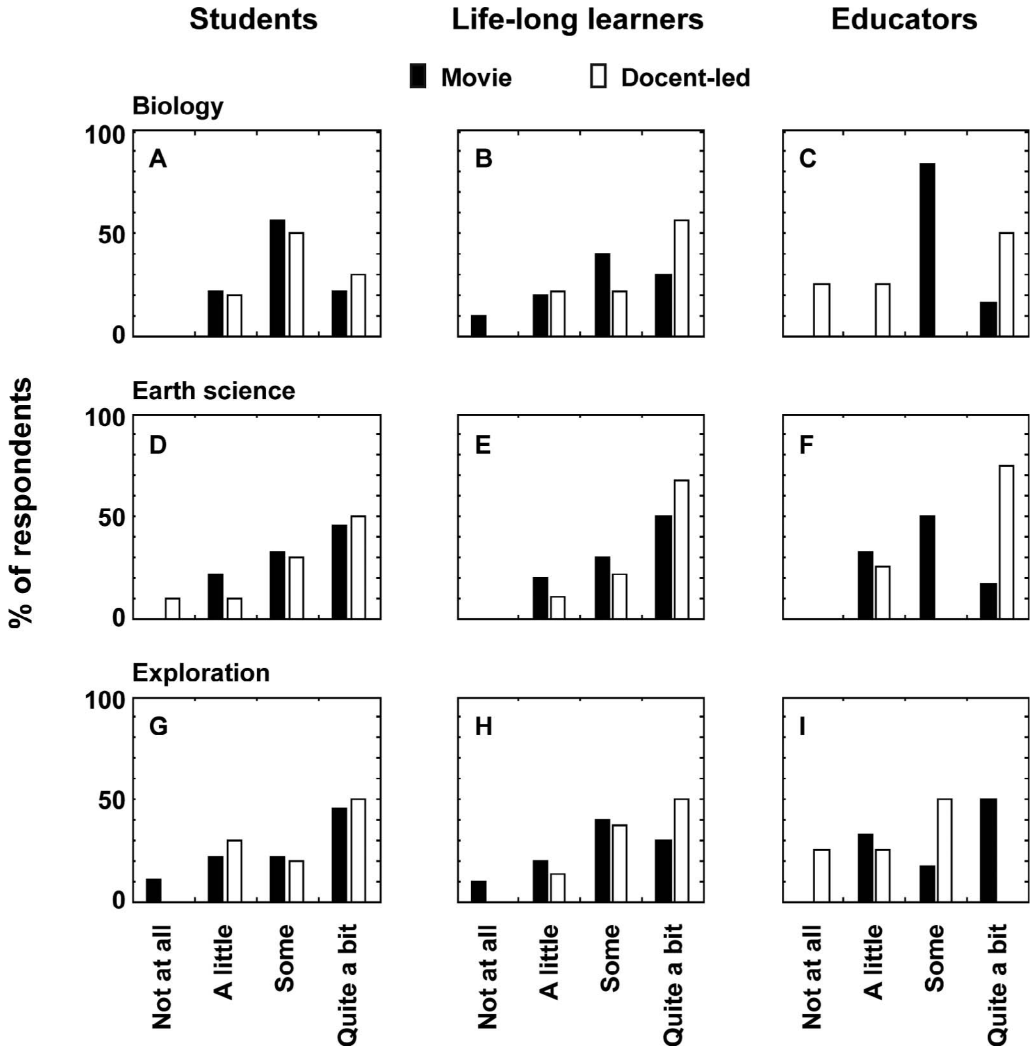

FIGURE 3: SFU narrative, perceived learning outcomes for three scientific literacy principles: upper (a–c), biology; middle (d–f), Earth Science; lower (g–i), exploration. Y-axis = percentage of respondents. (Left) Students (number of respondents, $n = 9$ movie, 10 docent-led), (center) lifelong learners [$n = 10$ movie, 9 docent-led, with the exception of 8 docent-led in (h)], and (right) educators ($n = 6$ movie, 4 docent-led).

represented populations may have led to an enhancement of perceived learning outcomes, given previous research correlating knowledge to socioeconomic status (Steel et al., 2005).

We did not find a significant difference between the effectiveness of the movie and the docent-led presentation for any of the literacy principles, but this may be expected because we tried to closely match the content and the script within the presentations. The SOS cross-site summative evaluation tested presentations categorized as facilitated, auto-run, or visitor-initiated and found that facilitation correlated with learning from SOS presentations (Goldman et al., 2010). However, in our study, we tested narrated compilation movies as another type of presentation, which differs from auto-run of datasets in the SOS Data Catalog; our movies tied together the datasets using narration, graphic art, additional imagery, and portions of the site-specific movies. Also, because we tried to closely match our compilation movies and docent-led presentations, our live shows were not as facilitated as they would be if tailored to specific audiences. Our results are more in line with a recent study using the SOS to teach climate literacy that found that short (5 min or less) narrated movies delivered within live shows yielded "a slight but not substantial advantage" over presentation of the same movie within an auto-run show (p. 485 in Schollaert Uz et al., 2014). Our study differs from Schollaert Uz et al. (2014) in that our live, docent-led presentations are intended to step more deliberately through the same datasets that are incorporated into our compilation movies.

Alternatively, it is possible that a statistical difference may be detected between our movie and our docent-led presentations with greater sample sizes and/or the use of more categories of responses. We might expect more learning from the docent-led presentation because the audience had more time to interact with the materials (20 min, as opposed to 5-min movies). Schollaert Uz et al. (2014) suggested that an advantage in learning from live shows could partly be because of slower pace and ability to repeat concepts. Within each group of respondents in our study (students, lifelong learners, and educators), some differences between the two types of presentations are apparent in the

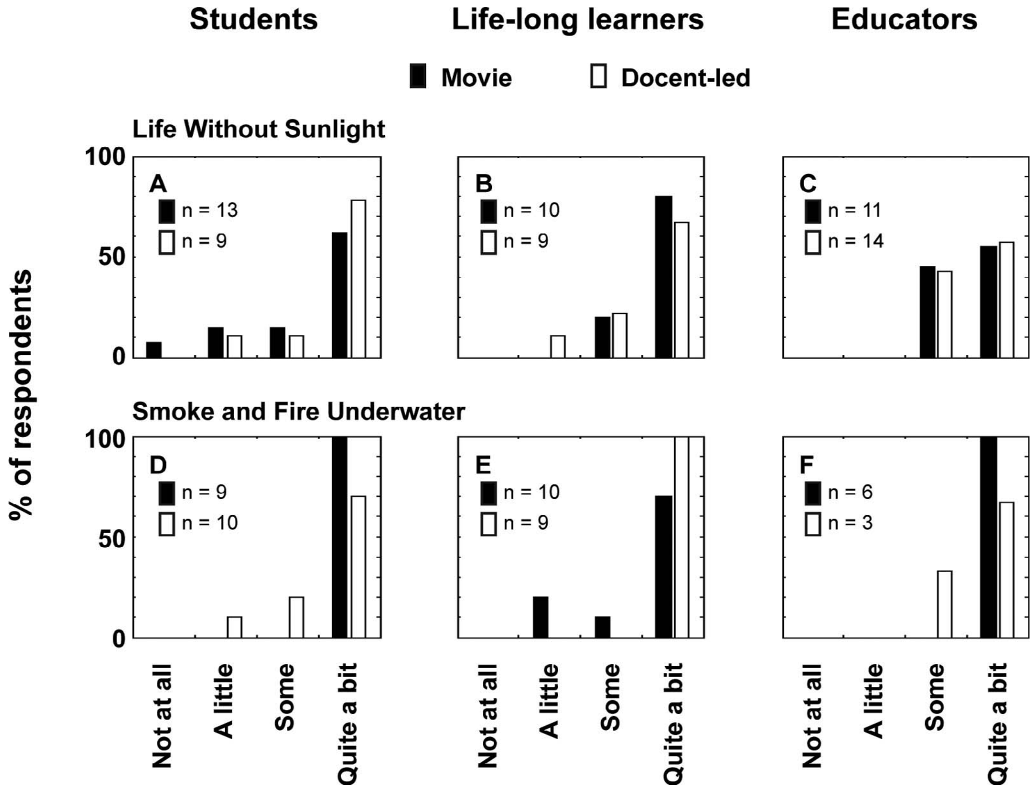

FIGURE 4: Excitement stimulated by SOS narratives: upper (a–c), LWS; lower (d–f), SFU. Y-axis = percentage of respondents; n = number of respondents. (Left) students, (center) lifelong learners, and (right) educators.

histograms, modes, and medians of responses to particular literacy principles in either narrative. However, no clear differences between the two types of presentations emerge for either narrative when considering all three literacy principles within a group (perhaps with the exception of lifelong learners responding to the docent-led presentation of SFU) or when considering a single literacy principle across groups.

Narrated compilation movies are a relatively new format for the SOS (Starobin, 2006), and we recommend additional research to better understand how to design movies to teach science with digital globes. When the cross-site summative evaluation was completed in 2010, only about a dozen narrated movies with SOS datasets were available, and as of summer 2015, about six times as many were available (NOAA, 2015). We think there are advantages when developing content for digital globes to produce a compilation movie, in addition to providing datasets and visualizations separately for facilitated, auto-run, and visitor-initiated presentations. An advantage of a movie is that the same carefully constructed information is delivered every time. A movie can aid docent training. There is inherent variability in a docent-led presentation in that the delivery depends on the individual docent's training, knowledge, and style and on the audience's interaction (e.g., questions from the audience). That said, it can be an advantage of the docent-led presentation for delivery to be tailored to the audience (e.g., repeat information and address questions from the audience). Also, a docent-led presentation can change over time to incorporate new scientific findings, while the movie may become outdated.

We recommend additional evaluation to compare learning of Earth system science that results from different spherical display systems, including virtual globes, and whether spherical technologies enhance retention of certain literacy principles. A key finding from the SOS cross-site evaluation was that "Visitors feel seeing information on the sphere is more realistic and provides more perspective" (p. 2 in Goldman et al., 2010). Schollaert Uz et al. (2014) found in free-response comments from SOS viewers that "seeing the huge Earth" and found that a school group retained learning 4 d after seeing a live SOS show or movie. Our compilation movies are available for other spherical display systems, including Magic Planet (http://globalimagination.com/) and iGlobe (http://www.iglobeinc.com). These digital globes are made in a variety of sizes, which may affect the audience's experience with the materials and consequent perceived or actual learning, as well as retention of learning. Digital globes are also being used in formal classroom settings and, to the best of our knowledge, have not been evaluated yet as part of a formal science curriculum.

As digital globes are increasingly being used in informal and formal education, we recommend more rigorous evaluation using pre- and posttest experimental designs to better understand the extent to which digital globes are effective in teaching Earth system science. Our posttest-only study was restricted to perceived learning outcomes; however, a pre- and posttest design with questions to test for correct responses before and after viewing content on the globe would allow quantification of actual learning to better assess the impact category "Awareness, knowledge or understanding (of)" (Friedman, 2008). A second posttest delivered some time later, for example, as conducted by

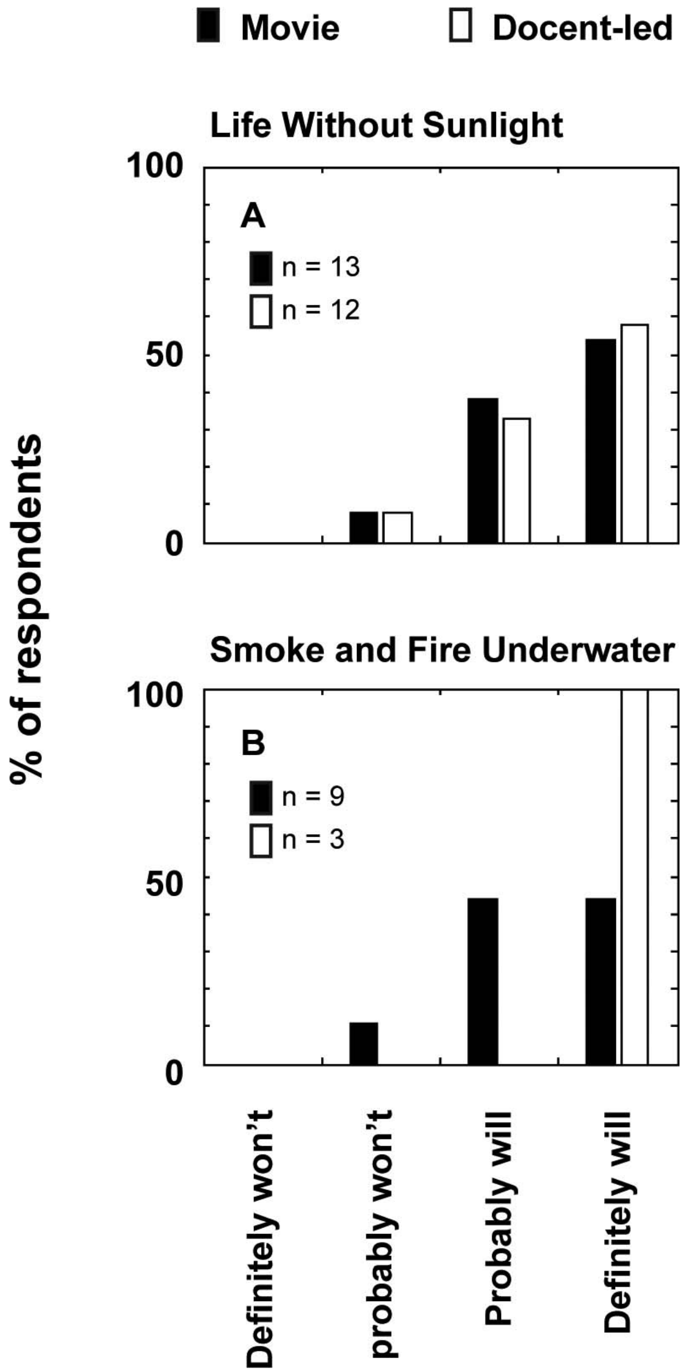

FIGURE 5: Educator responses to "Will you use what you learned today in your educational activities"? (a) LWS. (b) SFU. Y-axis = percentage of respondents; *n* = number of respondents.

Schollaert Uz et al. (2014), would quantify retention of learning from the digital globe.

Digital Globes Effective in Generating Excitement About the Deep Ocean Frontier

Our two narratives clearly generated excitement about the great unexplored deep ocean frontier and the exploration and research of deep-sea vents, and we attribute this success to the tight collaboration among scientists, educators, and graphic artists in developing the content for public audiences. In particular, we propose that the collaboration enhanced the storytelling and the visual impact of our materials. As explained on p. 14 in Ma et al. (2012b), scientists "cannot easily develop and produce high-quality visualizations" because of factors that include "lack of expertise in the fields of art, visualization, and storytelling." For example, in developing the narratives, we considered "narrative appetite" in which the audience "must want to know what happened" to continue to be engaged with the sphere presentation (p. 541 in Norris et al., 2005). We also considered carefully our audience as "interpreting agents," with previous research indicating that individuals construct their own meaning when interpreting a narrative by "inferring, construing, projecting, . . .anticipating" (p. 544 in Norris et al., 2005). In terms of choices made for visual impact, for example, initially we attempted to display imagery from deep-sea vents in a geographic context: in a rectangular image frame centered on the position on Earth where the imagery was collected. Ultimately, we decided instead to display the imagery on an entire hemisphere, which had the effect of looking at the scene as if in a fishbowl. The effect is similar to how the scene appears to human eyes through the thick viewports of deep-diving human-occupied vehicles.

Similar to our findings for the literacy principles, no clear differences between the movie and the docent-led presentation emerged for excitement when considering within a group or across groups. For example, the students were more excited by the docent-led presentation of LWS but clearly were more excited by the movie for SFU—and vice versa for the lifelong learners. Our results, however, are specific to the 6-ft-diameter SOS spherical display; to determine in general if digital globes are effective in exciting public audiences, we recommend evaluating content displayed on other, smaller systems.

Broader Impacts of Our New Content for SOS

The "95% solution," as coined by Falk and Dierking (2010), suggests that most STEM learning occurs in informal educational settings. Free-choice, science learning institutions have an important role in "promoting lifelong learning and nurturing environmental and ocean literacy" (p. 126 in Schubel et al., 2009). By contributing our new datasets, movies, playlists, and scripts to the SOS Data Catalog, we have the capability of providing our materials, tuned to ESLPs and OLPs, to more than 100 SOS facilities in 20 countries, reaching up to 33 million people per year (NOAA, 2014). In addition, our movies are available freely from an open-access server for other spherical display platforms and can reach many more people, especially as digital globes are incorporated into more settings—both informal and formal (Vanhoenacker, 2013).

In this project, we focused on reaching underrepresented students, and teachers of such students, in the Massachusetts South Coast region. We are hopeful that we not only educated and excited the students who participated in our study but also inspired a few next-generation ocean explorers and scientists. With teachers reporting that they are likely to incorporate their new learning into their classrooms, we are hopeful to extend the impact of the SOS presentations. We offered two free family nights to attract people who otherwise might not be interested in or able to afford a visit to a science museum; however, our future plans include adapting some of our materials for virtual globes to be able to reach people outside of the museum setting (e.g., Blaschke et al., 2012).

Acknowledgments

We would like to thank S. McCue from the National Deep Submergence Facility, K. Kostel from the Woods Hole Oceanographic Institution, S. Bean and J. Mitchell from the Ocean Explorium, the NOAA SOS Technical Team, and many scientific colleagues who helped in selecting imagery and providing information for the educational materials. The closing credits in our movies contain detailed acknowledgments. Funding for the Global Viewport to Deep-Sea Vents was provided by the National Science Foundation (No. 1202977) to S.E.B. and A.S.

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