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UniVRsal Access

Science Museums & Immersive Digital Technologies

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Executive Summary

In recent decades, immersive digital technologies have become a prominent part of science museum galleries. Today, science museum professionals can choose among a wide variety of experiences featuring these technologies, including those that make use of augmented reality (AR), virtual reality (VR), and projection mapping. But little is known about the considerations that influence these professionals' decisions on adopting a given digitally immersive exhibit. Without an understanding of the various factors that shape museum professionals' decision-making processes, experience designers may struggle to develop products that align with science museums' needs, goals, interests, and expectations.

To promote a deeper understanding of how science museum professionals think about digital technology as a tool for creating immersive experiences, this study shares on-the-ground insights from these professionals, highlighting what matters to them when considering the acquisition of new exhibits. Based on interviews with 16 science museum professionals who occupy a wide range of positions at institutions all across the US, our findings point to three important considerations that product developers should take into account when designing digitally immersive experiences.

First, instead of making technology the focal point of their exhibits, interviewees saw it as a tool to support STEM learning. Uninterested in "technology for technology's sake," when contemplating new experiences, they first think about the content they want to create and the learning goals they want to achieve. The value of immersive digital technologies, they agree, lies in the way they promote STEM learning through awe-inspiring, interactive, emotionally engaging experiences that spark curiosity and a desire for knowledge.

Second, interviewees said they prioritize digitally immersive exhibits that create positive experiences for visitors. Of chief importance to them are exhibits that promote social interaction and offer unique experiences. Given these priorities, interviewees indicated that immersive digital technologies are most effective when they are multisensory, interactive, and self-controlled. They also noted the importance of experiences that are accessible to people of various ages, different abilities / disabilities, and varying levels of STEM knowledge.

Third, interviewees highlighted the need for digital immersive exhibits that acknowledge their operational realities. Before investing in expensive digital technologies, the science museum professionals we spoke with said they need to be certain that these technologies have significant staying power, that they can be repaired by on-site staff when damage or malfunctions occur, that they can be leased to other museums without the need for modifications, and that they do not require the mass hiring of additional staff to provide instructions to visitors, monitor admittance, or clean equipment.

Through consideration of these three concerns, product designers can increase the likelihood that their immersive digital exhibits are adopted in science museums and that they successfully engage current and future audiences in positive STEM learning experiences.

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Introduction

Over the past twenty-five years, immersive digital technologies like AR, VR, and projection mapping have become an increasingly central part of the museum experience. In the early 2000s, some contended that the creation of digitally immersive worlds would prove useful—and *"maybe even necessary"* (Merritt, 2009)—to the industry's future competitiveness. While relatively few museums fully implemented immersive digital exhibits back then, studies of museums that did experiment with emerging technologies showed that these exhibits yielded high levels of engagement and enjoyment among visitors (Damala et al., 2008; Hall & Bannon, 2006; Szymanksi, 2008). In the 2010s, researchers began to uncover evidence of the numerous ways in which immersive digital exhibits can facilitate knowledge acquisition and the development of critical thinking skills (Li & Chang, 2017; Sommerauer & Müller, 2014; Yoon et al., 2011; Yoon et al., 2014). Since then, a robust body of literature has emerged documenting the positive impacts of digital immersion on museum learning (Goldman & Pope, 2023; Mercan et al., 2023; Shahab et al., 2023; Zhou et al., 2022). These findings have helped fuel more widespread acceptance of digitally immersive technologies, as all around the world, museums are designing and implementing exhibits that make use of these technologies (Hutson & Hutson, 2024; Richardson 2024).

This trend is particularly true of science museums, which have long been sites of interactive and immersive learning and have a long history of testing and adopting emerging technologies (Jasmine et al., 2024). Given that science museum professionals now have access to a wide variety of digitally immersive experiences, understanding the various considerations that inform their technology adoption decisions is of critical importance. What are science museums looking for when they assess different kinds of digitally immersive technologies? Which experiences are likely to be adopted, and how will their use and implementation change as newer technologies emerge?

To date, relatively few studies have addressed questions like these, as much of the literature on immersive digital technologies in museums foregrounds visitor expectations and experiences (for important exceptions to this, see Fernandes & Casteleiro-Pitrez, 2023; Schettino, 2016; Shehade & Stylianou-Lambert, 2020). Complementing these studies, this report shares on-the-ground insights from science museum professionals and is geared toward helping external technology developers and product designers create experiences that align with these professionals' needs, interests, and expectations. Understanding the considerations that guide science museum professionals' decision-making processes will help developers and designers determine the kinds of digital technologies worth investing in, leading to more successful digital immersion experiences.

This Report

This report builds on our evaluation (Barchas-Lichtenstein et al., 2024) of UniVRsal Access, an NSF-funded collaboration between the Educational Gaming Environments group (EdGE) at TERC and Landmark College aimed at designing an inclusive virtual reality (VR) STEM experience for neurodiverse users. Working with game developers MXTReality, the co-design team created *Europa Prime*, an immersive VR experience that transports players to a future in which humans have reached Europa. In late 2023, we conducted user testing and think-aloud protocols with 40 adults who played *Europa Prime* at two different science centers.

Findings from this user testing indicated that *Europa Prime* was a fun, engaging VR experience—one that invoked feelings of awe and wonder in participants and that piqued curiosity around multiple STEM topics. Impacts on STEM learning were mixed. While users with little prior knowledge of Europa or space exploration generally learned some basic facts, many struggled to differentiate between aspects of the experience that were factual, probable, and entirely speculative. Participants with deeper prior knowledge did not learn any new facts, but they came away from *Europa Prime* able to articulate the facts and theories that undergirded many different aspects of the experience.

Having examined *Europa Prime*'s effectiveness from a user perspective, in this study, we explore the perspectives of science museum professionals. Specifically, we look into the feasibility of installing digitally immersive exhibits (either VR-based or otherwise) using *Europa Prime* content in science-oriented museums. The idea for this study originated when we and the project team at EdGE began hearing anecdotal reports about waning use of VR technologies in science museums (particularly after COVID-related closures in 2020, when concerns about cleaning devices and staffing costs came to the forefront). Although *Europa Prime* was created as a VR experience, its content and experience design could also be adapted to align with other formats that might be more commonly used in science museums, including projection mapping and digital domes. Determining other means of disseminating this experience required a better understanding of the typical use of digitally immersive technologies in science museums, and of the design considerations science museum professionals take into account when selecting experiences for their galleries.

To promote a deeper understanding of how science museum professionals think about digital technology as a tool for immersive experiences, this report addresses three overarching questions:

- What is the role of immersion in science museums?
- What digital technologies are available for science museums to use to create immersive learning experiences?
- How do science museum professionals choose digital tools for immersion?

Considering the first of these questions, we look at how science museum professionals define immersion, and share their thoughts on how immersive designs facilitate learning. With regard to the second question, we look at different kinds of emerging technologies and discuss how science museum professionals are learning about them. And for the last question, we describe the different kinds of design considerations that inform science

museum professionals' evaluation of digitally immersive options, including their assessments of where immersive digital technologies may fall short.

Methods

To gain insights on how the content and design choices of *Europa Prime* could be adapted to align with the current and future needs and interests of science museums, we conducted semi-structured interviews with 16 science museum professionals experienced in the design or development of digital immersive experiences. Questions focused on what professionals viewed as an immersive experience, what they saw as the value of such experiences, how immersive digital technologies are and could potentially be used in museums, and what factors contributed to the effectiveness and adoption of immersive technologies. The study used a snowball sampling design in which interviewees were asked to recommend others in their professional networks who might be able to participate. While snowball sampling does not yield fully representative samples (a factor that limits the generalizability of findings), it can be helpful for reaching highly specific populations (Frank & Snijders, 1994). Our initial set of 10 interviewees represented a broad range of perspectives in the field, including science museums of varying sizes (small, medium, and large), types (science centers, natural history museums, planetariums, and discovery centers), and geographic regions in the US.

Tables 1-3 below show the breakdown of interviewees by region, the different organizations they work for, and the size of the respective institutions.

Table 1. Interview Participants by Region

Northeast	Southeast	Midwest	Southwest	N/A
6	1	5	2	2

Table 2. Interview Participants by Organization Type

Natural History & Science	Science	Science & Technology	Design Firm	Museum Complex
6	5	2	2	1

Table 3. Interview Participants by Size of Facility

Small	Medium	Large	N/A
2	2	11	2

Note. Sizes were calculated on the basis of square footage, using the Association of Science & Technology Center's categorization scheme. According to this, small facilities are those under 25,000 square feet, medium-sized ones are between 25 and 50,000 square feet, and large facilities are those over 50,000 feet.

In parallel with these interviews, we also held three focus groups at three science museums in the northeastern US. These museums differed in size, educational philosophies, and usage of immersive technologies. At each museum, 3-6 staff members involved in exhibit design engaged with the *Europa Prime* VR experience before participating in a one-hour discussion focusing on how elements of the experience could be adapted for use in a

science museum context. During these focus groups, we spoke with a total of 13 additional museum professionals.

The data from these interviews and focus groups (*N* = 29) can inform adaptation choices aimed at repurposing *Europa Prime* content into formats that align with participants' understandings of high-quality museum experiences. More broadly, findings from this study also provide design guidance and advice for any professional looking to create immersive digital experiences for implementation in science museums.

Analysis

We used the techniques of thematic analysis (Nowell et al., 2017) to identify themes and patterns in the data. To familiarize ourselves with the data, our research team first read the interview transcripts and noted initial themes that could be investigated through further analysis. Our team then generated a series of overarching themes and coded the data from each interview according to those themes. After completing the initial coding, we further discussed the data and identified new patterns and sub-themes to investigate. We then re-coded the data, discussed the new patterns and themes, and generated a final interpretation. Our research team included individuals who were relatively new to the field of science museums and one researcher who has worked in science museums (and exhibits in particular) for multiple decades. The use of multiple researchers with varying levels of familiarity with the field aligns with practices for promoting trustworthiness in findings from qualitative research (Lincoln & Guba, 1985).

To provide direct insights into the thoughts and perspectives of the participating museum professionals, data interpretation prominently features direct quotes from interviewees. These quotes have been edited lightly for readability (e.g., removing disfluencies) and anonymization (e.g., removing names of individuals and museums)—a key consideration for a relatively small and highly networked field.

Findings

What is the role of immersion in science museums?

Defining immersion

The science museum professionals we spoke with consistently defined an immersive experience as one that reduces visitors' awareness of being in a museum. They explained how immersive exhibits take people *"somewhere else"* and cause their external surroundings to *"float away."* Likening them to theatrical productions, participants defined immersive exhibits as *"heavily designed environments"* that *"completely subsume [visitors'] attention."* Just as a movie or theatrical performance can cause audiences to become *"so caught up in the experience"* that they forget their actual physical location, participants described the immersive exhibit as something people *"can get lost in."* By creating a storyworld that visitors can *"feel [all] around [them],"* the immersive exhibit offers a *"full sensorial experience"* that transports people *"into another realm."*

Key to that experience, participants agreed, are environments that engage multiple senses. *"It's not just something that you're looking at with your eyes,"* one participant shared, *"it's something that you're moving through and engaging with physically."* Echoing this definition of the immersive exhibit as *"a mind-body experience of content,"* another participant added that these experiences were typically both visual and auditory and could also include movement and even smells. *"It's a very intensive way of learning by experiencing the knowledge,"* one participant explained. The *"multi-sensory"* exhibit, said another, *"captures you a bit more than a traditional exhibit might."*

Participants were careful, however, to note that *"traditional"* exhibits can also be immersive. For example, the participant (above) who compared immersive exhibits to *"traditional"* exhibits also stated that immersive exhibits encompassed a range of experiences—from a *"desktop activity that just really grabs your attention"* to an IMAX film to a headset activity to an *"old school diorama."* Employing a similarly expansive definition, another participant shared that while many people equate it with digital experiences, immersion is *"really much bigger and broader than that." "I think that there are many ways to make an immersive experience,"* said a third participant, adding that many of the technologies used to create immersive museum exhibits today are *"just digital extensions of what we've been doing in the physical world for a long time."*

How immersion facilitates learning

Somewhere you can't go

Participants concurred that digitally immersive exhibits have great potential as vehicles for education. In keeping with research showing that *"novel contexts and ideas stimulate a lot of learning,"* they argued that these exhibits facilitate learning by *"snap[ping] you out of your normal day to day"* and encouraging consideration of *"different framing[s] and*

worldview[s]." Participants shared how the process of journeying to *"different environments"* and experiencing places *"you don't usually get to go"*—whether it be *"taking a raft on the Grand Canyon,"* traveling aboard *"a ship in orbit around the Earth,"* or traveling back in time to see what life looked like *"thousands of years ago"*—captivates visitors' attention, sparks their curiosity, and creates memorable experiences that generate excitement around different topics. All of this, they agreed, lays a foundation for learning. As one participant shared: *"once you capture their attention, they're engaged, [which is] step one to learning."*

Awe, wonder, and curiosity

Participants regarded immersive digital technologies as particularly well-suited to generating excitement for learning. Speaking to this, one participant shared an example of taking their son to a VR exhibit at a museum. *"Had I told him 'we're going to learn about this really important part in British history',"* the participant recalled, *"he would have been like, 'snooze.'"* But instead, they told their son that *"we're going to do VR, and it's going to be in a quest format."* In the end, this turned out to be *"one of his favorite experiences."* Recalling exhibits where *"you were all of a sudden underwater or in outer space,"* another participant said that digital immersion promotes knowledge acquisition first and foremost by *"excit[ing] you and get[ting] you interested in learning."*

Relevance and empathy

One of the ways digitally immersive exhibits can stimulate interest, participants observed, is by giving visitors real-world, action-based motivations for learning. One participant discussed an experience that did this by making climate change personal. Transporting museum-goers to Venice, Italy, this exhibit asked visitors to contribute to the building of blockades designed to combat sea-level rise within the city:

> *They have doors that are for shops, and you have the shopkeepers, they're saying, "the floods are coming, help us help us." And you have to build the blockades to protect their shop from the rising water level [...] it puts you there, it becomes that much more important. And so you care about what's going on. And you understand the importance of what you're doing. You're not just building a dam for the sake of building a dam; you're building a dam to protect these people who are talking to you from this thing that you can see happening. It puts a whole different feel to that experience, in terms of being meaningful.*

Commenting on the value of exhibits like this, another participant highlighted their ability to *"build empathy"* and help people *"care about [things] enough to take care of [them]."*

Exploration and Discovery

From an educational standpoint, participants agreed that exploratory experiences are more important than sharing information. Cautioning that digitally immersive exhibits should *"not [be] too didactic,"* they contended that the best examples of these were *"a lot less about content and more about having an experience."* In other words, instead of imparting knowledge through labels, narration, or other kinds of direct explanations (such as, *"here's the physics of how and why this works"*), participants thought that digitally immersive exhibits most effectively facilitated learning when they *"spark the kind of interest that might cause [visitors] to get into a deeper, more academic level elsewhere."* As one participant

said: *"you want the learning goals to be something that you can just pick up on sort of implicitly, from interacting with it."*

As a component of a larger exhibit

While participants highlighted immersive digital technologies as key to generating excitement and engagement, they also drew attention to other factors that contribute to learning. Among these were other spaces within the museum. Many participants viewed immersion as *"complementary to a broader exhibit experience,"* believing that combining these with non-immersive exhibits and *"real artifacts"* constituted a *"really powerful one-two punch"* that could make learning more *"concrete."* One participant spoke of how a digitally immersive experience was *"preceded by a somewhat traditional intro exhibit"* that helped visitors understand and prepare for immersion. Sharing a similar example, another participant noted that by pairing digitally immersive exhibits with non-immersive ones, *"you can then reinforce that learning by actually doing things that relate to what you just learned."*

Science museum staff are also vital to the learning process, as they can ask and answer questions related to visitors' immersive experiences. One participant described how facilitators contextualized a VR program for school groups in which students built red blood cells. After completing this, staff provided a wrap-up of the experience, asking visitors what they noticed and sharing information about the functions these cells perform within the body. By *"zero[ing] in on some of the unique things the app explored,"* facilitators deepened the educational value of this experience.

What digital technologies are available for science museums to use to create immersive learning experiences?

Formats

In keeping with their broad, expansive definition of immersive exhibits, science museum professionals did not see digital technologies as necessary for immersion. They noted that built environments and *"object theaters"* can give visitors many of the same multisensorial experiences as digitally immersive exhibits. One participant described how a glacier exhibit that included partially chilled fiberglass plates effectively simulated the experience of being in an icy environment. Another mentioned a physical recreation of an old weather station, which shook to simulate high wind speeds.

The most commonly mentioned digitally immersive technologies were virtual reality (VR), augmented reality (AR), projection mapping, and large-screen video. Examples of **VR** in museums included headset experiences and simulator rides. Headset experiences included both 360 video and fully interactive games, while simulator rides such as Birdly® are vendor-created products that museums can buy or rent. **AR** was often brought up as a way to provide additional context or content for a physical exhibit. While this can involve museum-provided devices, the most common example of AR was an application on visitors' phones.

Participants also explained how **large-screen videos** could be used on walls (to create an immersive room), in a planetarium dome, or in an IMAX theater.

Projection mapping is a technology many science museum professionals were excited about. Beyond simply projecting onto walls, it can be combined with **motion sensing** to create environments that respond to visitors' movements or used on exhibit elements to do things like highlight specific bones on a dinosaur skeleton or "look inside" a life-size elephant model. Several participants were enthusiastic about exhibits such as these, which use technologies to combine physical objects with digital components. As an exemplar of this kind of experience, many participants mentioned the Connected Worlds exhibit at the New York Hall of Science, in which visitors' interactions with physical objects like foam logs affect the ecosystem projected around them. Participants also described how digital technology could enhance physical exhibits: displaying a digital grid so visitors can plan a path for a physical rover, or vice versa, a physical space shuttle visitors can enter with a digital landing simulator game on the cockpit screen.

Learning about emerging technology

To stay aware of current trends in technology that could be applied to create immersive environments for visitors, participants said they draw on a wide range of sources. They learn about emerging technologies by attending museum conferences (where these technologies may be exhibited), by visiting other museums (including both science and art museums, along with exhibitions such as those created by TeamLab and Meow Wolf), by going to theme parks (which often make use of higher-budget immersive technologies, and as such, are a good place to glimpse future possibilities that are currently unaffordable and/or impractical), and by talking with peers in the informal learning space. For information about future technologies, participants mentioned following research groups such as the MIT Media Lab. Lastly, they described their attempts to keep abreast of developments in the world of consumer products, noting that in some cases, technologies initially designed for commercial purposes may be well-suited for other uses. As an example, one participant mentioned how Microsoft's Kinect (an input device for gaming) included a *"really cool camera with a lot of applications"* which was adopted by science museums to create digitally immersive exhibits (e.g., Mizuno, Tsukada, & Uehara, 2017).

How do science museum professionals choose digital tools for immersion?

Design considerations

Learning goals

Almost all of the science museum professionals we interviewed emphasized the importance of choosing technologies based on identified learning goals. They discussed a wide range of such goals—from making visitors *"interested enough to go off and learn more about a subject"* to *"giving kids the ability to imagine and to create"* to *"helping people understand the vastly changing network of science and technology."*

Participants agreed that these goals are often informed by the overall experience each museum offers. Aware of the fact that *"[people are] here to visit the museum, not just this one experience,"* participants spoke of how they consider ways to make new exhibits *"meaningful with the context of the museum"*—for example, by aligning them with a museum's existing focus areas. *"What we think about first,"* one participant said, is *"our strengths."* *"For us,"* they continued, *"it's aviation, astronomy, [and] earth and space science."* Along similar lines, participants spoke about how they work to create connections between the *"big ideas"* different exhibits are putting forward. Science museum professionals also consider *"the pacing of experiences"* as visitors move through the facility. *"You're trying to build a narrative about the subject at hand,"* one participant shared, *"and then trying to take [visitors] through an emotional ride for 7500 square feet."*

Scientific accuracy was another paramount concern for participants. As science is *"the inspiration and the motivation"* for the exhibit, participants agreed that making the content of digitally immersive exhibits consistent with existing scientific knowledge is a critical prerequisite for promoting learning. As one participant said: *"you do want to make it so that they are engaging with the real object, the real phenomenon."* Agreeing with this, another participant shared that *"it can't just be a cool experience."*

The science museum professionals we interviewed were in agreement that planning for new museum experiences does not begin with technological considerations. *"We never start with the technology,"* one participant shared, adding that *"this is the biggest mistake people make"* with regard to science museum professionals' exhibit-related priorities. Only after figuring out *"what you are trying to convey and why"* do science museum professionals turn to consider how *"technology can be a part of that."* The first step in the process, one participant said, is *"figur[ing] out what my content is."* The second step is determining *"what the right technology is to communicate that content."* In all cases, science museum professionals *"don't want the technology to be the point of the exhibit."* As one participant put it, the most important question for museums is, *"Is it a true learning experience or is it just a gee-whiz experience?"*

Visitor experience

Unique, social experiences

When discussing how they plan new exhibits, participants also highlighted the importance of offering visitors experiences that are unique and social. One of their biggest concerns is creating experiences that *"you can have only in the museum"*—that is, experiences that are different from what a person could be doing *"at home on their couch."* Aware that at times their *"biggest competition"* is home-based forms of entertainment and education (including Netflix, nature documentaries, or various iPad apps), these professionals are always asking themselves questions such as *"what makes it special to be [at the museum], now, at this time?"* In terms of *"motivat[ing] people to come,"* they know that visitors often *"want to go have a good time with family."* As such, they saw it as crucial for them to create experiences that are participatory and allow visitors to interact with others—*"whether it's the people that [they] came with"* or *"other people who are [at the museum]."*

It is for this reason that participants were less excited about the use of VR as a tool for digital immersion. Exhibits that create a *"solitary experience"* can be *"very isolating,"* participants explained. And because *"most VR experiences are individual experiences,"* they regarded this technology as problematic. Instead of being *"locked in a zone with something on [their] head,"* the science museum professionals we spoke with indicated a preference for technologies aligned with their goal of *"always trying to get people to interact."*

Accessibility

According to the professionals we interviewed, one reason museums favor exhibits that facilitate shared, group experiences is that families are among their most common visitors. As such, these professionals prioritize experiences that engage a wide range of audiences—*"from little kids to adults and professionals and scientists."* An exhibit *"doesn't have to communicate the same thing to everybody,"* one participant shared. Ideally, exhibits give both children and adults something to do and allow both groups to *"learn something so they become an expert"* on a topic.

In addition to creating exhibits that speak to the needs and interests of different age groups, these professionals also shared how considering accessibility takes language barriers and costs into account. Speaking to the first of these concerns, one participant noted that many visitors *"don't speak English as their first language or at all."* If translating text is difficult or impossible, they added, this becomes a *"roadblock to somebody being able to successfully enjoy an experience."* With regard to financial obstacles, one participant is always asking if a new exhibit is going to be *"something that only those who can afford the extra ticket are going to be able to enjoy."* Speaking about phone-based activities, another participant stated that *"phone access is a problem in our community sometimes, and we want to be as open and inclusive as possible."*

Participants also consider the impacts (both positive and negative) of digitally immersive exhibits for people with disabilities. Several highlighted examples of how these exhibits might exclude visitors with disabilities. *"If you're not paying attention to that,"* one said, visitors who are on the autism spectrum or who have sensory processing challenges might experience *"overload"* when participating in these exhibits. And as *"a lot of the[se] experiences are geared toward sight,"* one participant remarked, it is also important to think about how to make these exhibits work for *"people of all different ages who aren't able to see."* At the same time, participants noted how the multisensory nature of immersive experiences might create a more welcoming, inclusive space for people with disabilities. *"When we're able to put these tactile, audible, or visually engaging experiences forward,"* one participant observed, *"then we can also engage people who might feel that many places are not ideal for them."*

Ease of use

Related to participants' concerns about accessibility were those around potential barriers to entry. Interfaces that are unfamiliar or that require significant instruction tend to *"lose people"* and *"get in the way of learning,"* participants explained. And as visitors are often *"exhausted"* going through the different halls of a museum, asking them to *"spend brainpower trying to figure out how to play a game"* is difficult to justify. Given this, one participant recommended the use of already existing technologies (for example, UX/UI

languages that have been developed for touch devices) to help visitors *"get over that hump as quickly as possible."* The goal, this participant said, is to *"get to a point where our digital exhibit elements are as intuitive and easy to engage with as our physical exhibits."*

Participants also identified barriers related to comfort and safety. With regard to VR headsets, they noted how there is *"an additional hurdle to climb when you're putting something on someone's face"*—to say nothing of the discomfort experienced by *"those who are prone to motion sickness or vertigo."* In the case of AR, participants identified an effort-related barrier—for example, unwillingness to download apps. As one participant explained, this *"is a tricky thing to get people to want to do on their personal devices."*

Interactivity

Participants also emphasized the importance of interactivity. They agreed that if visitors are simply *"sitting," "just watching another screen,"* or listening to *"a talking head,"* they *"will abandon [the exhibit] like crazy."* While some saw a place for more atmospheric uses of immersive technology (for example, large scale projection mapping where environments are *"washing over you as you're moving to and through things"*), participants generally cautioned against passive experiences. *"You have to make sure that the visitor is an actor in it,"* one shared. Highlighting this need to give visitors agency, another participant pointed to the value of exhibits that are *"self-controlled,"* giving visitors the opportunity to progress *"at [their] own pace."* By engaging visitors physically, mentally, and emotionally, participants agreed, interactive exhibits can help visitors retain some of what they learned when they leave.

Finance and operations

Development, setup, and maintenance costs

Many of the science museum professionals we interviewed observed that large-scale digital immersive experiences are expensive to develop, making their purchase and use *"potentially dangerous."* Participants noted that while science museums are *"bringing in good money,"* they are often *"spending at the same rate we're bringing it in,"* and *"don't have a lot of extra"* for digital technologies that can *"double and triple"* the cost of their exhibit spaces. Given this, when considering investments in digitally immersive exhibits, participants discussed how they often weigh a number of different variables.

One is staying power. Before introducing new technology, these professionals and their museums ask themselves questions such as *"Is this thing I'm investing in going to still be a thing in five years?"* They also consider the extent to which other nearby venues might be interested in leasing a given exhibit. *"One museum investing in a piece of content that only their museum can use,"* one participant explained, *"is a really high bar."* Smaller museums can typically only lease exhibits or pieces of equipment. Because of this, one participant said that traveling exhibits are sometimes preferable. In order for these to work effectively, however, science museum professionals need to be able to easily reconfigure the exhibit's settings so that they can be customized to individual museum spaces. As one participant said, *"You can't rely too much on outside, highly paid tech labor to come in and set up the show. It's just too expensive."*

Participants also highlighted durability and ease of troubleshooting as important concerns. Recognizing that *"the more cutting-edge [the] technology, the more breakdowns you're going to have,"* participants explained how damage caused by visitors (whether accidental or intentional) or during transport can render exhibits inoperable. According to participants, when this happens, many museums (especially smaller ones) lack in-house digital content experts and cannot afford the costs of bringing in third parties to *"do all of the repairs."* As such, participants recommended that exhibits be *"user friendly"* so that staff can be *"trained in how to keep [them] up and running."* As one participant explained, *"if you can't keep them working, there's just no point"* to creating these exhibits.

Staffing

When evaluating options for digital immersion, science museum professionals also consider how staff-intensive a given exhibit will be. Participants reported that many digitally immersive exhibits require museum staff to guide visitors through an experience, provide instructions, and—in the case of VR headsets—clean equipment. If the exhibit is run as a theater, then staff will also be needed for taking tickets and admittance. Given that *"there are not endless numbers of staff who are able to help visitors"* and that *"staff aren't free,"* participants regarded some digitally immersive experiences as cost prohibitive. This was particularly the case for VR, which one participant called *"an enormous investment in resources."* VR exhibits often require *"multiple service representatives"* to be present *"at all times,"* this participant explained, adding that because of this, they *"would rather use this floor space for something else."* Echoing this, another participant said that on account of their limited staffing capacities, they would be *"hard pressed to do another headset experience."*

Throughput

Another chief concern for science museum professionals is the number of visitors their exhibits can accommodate. In part, this concern is financial: as one participant shared, *"you have got to push enough people through there to pay for the staff and the overhead."* But visitor satisfaction is also an issue. Digitally immersive exhibits that only allow one person to move through at a time can cause *"giant backups"* that are *"frustrating"* for visitors—particularly when these break up families or other groups. These backups are especially problematic for VR exhibits. Although some participants had experience with VR simulators that allow multiple guests to ride simultaneously or with in-headset apps with capacity for up to 20 attendees, they noted (as one put it) that VR exhibits *"don't accommodate as much as a large, immersive venue."* By contrast, they described AR, projection mapping, and large-screen experiences as both accommodating more people and requiring less downtime between groups.

Why technology fails

Technology for technology's sake

When exhibits prioritize technology over content, participants warned, they often fail to facilitate learning. Articulating a common sentiment, one participant said that *"the biggest drawback [of digital immersion] is [that] there is a tendency to fall in love with the technology for technology's sake."* As an example of this, many participants discussed the

multiple *"immersive van Gogh experiences"* that have emerged in recent years. While the initial version of this used *"incredibly high-res scans of paintings"* that enabled viewers to see things like *"the depth of the paint,"* subsequent iterations used lower-quality digital assets that failed to enable any new insights into the art itself. As another example, one participant mentioned IMAX. *"For the first 10 to 15 years"* after this product emerged, they said, people were *"so enthralled with this technology that the actual film was almost secondary." "I'd hate to see museums get so enthralled with the technology that they're not focused on the educational experience,"* this participant added. Echoing this concern, another participant warned against technologically-driven exhibits that are *"just too fluffy." "There's a fine balance between just throwing tech at everything and assuming that's going to make it cool,"* they said, and *"really developing something that's a strong product with strong content."*

Another problem with using digital technology as a selling point, participants cautioned, is that it may lead visitors to compare museum exhibits to other, much higher-budget digital experiences. *"We will ultimately not be able to compete with someone like Disney or lots of commercial places that are going to do immersive things,"* one participant said. *"What we can compete with,"* added another, *"is content." "So whatever you do, don't try to compete directly with what's in the commercial marketplace."*

Fads fade

Fading novelty of digital formats is another concern science museum professionals voiced about immersive experiences. If designers hope to make these experiences appealing through novelty, participants said, they will need to guard against visitor fatigue. Once a trend has become saturated, museum-goers may lose interest, thinking *"I've kind of seen and done it."* The goal, one participant shared, is to create *"different enough experiences so that people don't say 'Oh, it's another big projection thing' or 'Oh, it's another reactive wall.'"* At times, the feeling of novelty can fade even within a single visit. One participant discussed an exhibit in which images projected from gobos (tools that filter light into different shapes or patterns) *"explode[d] into little petals"* when visitors interacted with them. At first, visitors enjoyed this experience, but as the exhibit *"kept doing a different variation of that one track,"* they lost interest, thinking *"Oh, I get what I'm supposed to do, and, eh."*

If jumping on the bandwagon too late risks audience fatigue, participants explained, trying to adopt trends too early can also be risky—especially if they fail to take off. As an example, one participant mentioned QR codes, which failed to make inroads when initially introduced and only became popular when they were integrated with cameras (rather than requiring a dedicated scanner app). Others also cautioned against the early adoption of unproven technologies. *"I think museums are really great at putting a bunch of dollars into something that doesn't work,"* one participant shared, *"and then they're sucking wind for years afterwards."* As a general principle, this participant said that the best practice is to make sure that the tool that's been chosen *"is going to deliver what you need before you start using it."*

Resistance to screens

Some science museum professionals noted how screen-based experiences (especially post-COVID) have become less compelling over time. *"A lot of [visitors] have had enough of screens,"* one participant said, adding that the need to *"move and touch and manipulate things"* has drawn many visitors to *"lower tech exhibits."* Others echoed this finding, saying that *"we've seen our audiences turn away from screens."* According to participants this shift is particularly strong among young children, but other audiences have also developed a preference for physical or hybrid physical/digital immersive experiences. One participant cited a visitor study they had conducted showing that *"people don't actually want to use their phones in museums."* This reluctance to rely too heavily on immersive digital technologies, another participant shared, was tied to the belief that museum exhibits should not *"duplicate what you have already in your home environment or gaming environment."*

Discussion

When it comes to science museums, digital immersive technologies are here to stay. The science museum professionals we spoke with believed that these technologies can be used to effectively engage visitors and facilitate learning. Yet although these professionals were committed to learning about, experimenting with, and implementing digitally immersive exhibits within their respective museum spaces, they did not offer an unconditional, across-the-board endorsement of immersive digital technologies. Instead of pursuing *"technology for technology's sake,"* they agreed that digitally immersive experiences should be adopted when they align with a museum's broader needs, interests, and expectations. Their remarks point to three factors that product designers and developers should consider when creating digitally immersive exhibits: learning design, visitor needs and interests, and museum operations.

In what follows, we offer three general recommendations related to these factors and discuss how they apply specifically to *Europa Prime*.

Leverage the transporting, awe-inspiring, interactive, and emotionally engaging aspects of immersive technologies to promote science learning

When selecting experiences for their galleries, the science museum professionals we spoke with agreed that learning and experience goals are always a primary consideration. They think first about the learning goals they want to achieve and then select the experience that best aligns with those aims. They question the idea of technology for technology's sake, and are wary of technological fads that may come and go as visitors' expectations change. Instead of trying to create *"cool"* experiences that make immersive digital technologies the focal point of an exhibit, they emphasized how these technologies should facilitate learning by generating excitement, promoting a sense of awe and wonder, and encouraging exploration and self-directed discovery. Given their emphasis on creating strong content, they prioritize scientific accuracy in exhibit design, agreeing that experiences should reflect the state of contemporary scientific knowledge around a given topic.

In light of these findings, designers should consider what immersive digital technologies are best at achieving, and design experiences that leverage the educational strengths of these technologies. According to the professionals we interviewed, digital immersive experiences most effectively promote learning when they transport visitors to times and places they would otherwise be unable to visit. By exploring and interacting with these new environments, they said, visitors' curiosity is piqued in ways that stimulate their interests in a given topic and facilitate the discovery of new ideas. And once engaged in this manner, visitors are primed for exploring other aspects of the museum, including physical interactives and collections. In their comments, participants emphasized the importance of integrating digitally immersive exhibits into the overall context of the museum in ways that deepen existing focus areas.

How this applies to *Europa Prime*

One of the key strengths of the *Europa Prime* experience is the way it transports users to another time and place. As Europa is currently outside of humanity's reach, the experience takes place in the distant future. The participants we spoke with in our evaluation of *Europa Prime* (Barchas-Lichtenstein et al., 2024) regarded the experience as exciting and inspiring, describing it with words such as *"truly wonderful," "spectacular,"* and *"really beautiful."* Full of visually stunning scenes and breathtaking views, *Europa Prime* is excellently positioned to leverage awe and wonder in support of STEM learning. While some participants did not report a sense of awe or wonder, a number indicated that *Europa Prime* had stimulated a desire to seek out information on Europa and learn more about space exploration and astrobiology.

As this indicates, aspects of *Europa Prime* align with what science museum professionals want from an immersive digital experience. However, as we noted in our evaluation (Barchas-Lichtenstein et al., 2024), one drawback of the experience is that visitors do not always know what is fiction and what is reality. Though *Europa Prime* contains embedded factual information about Europa that visitors can access through their exploration and interactions with the environment, participants struggled to distinguish this from the more speculative aspects of the experience. In order to meet science museum professionals' expectations in terms of scientific accuracy, *Europa Prime* would benefit from drawing clearer lines between what is currently known about Europa, what is likely to be true about Europa, and what is entirely speculative. Clarifying such details would be important for creating an experience that promotes science learning.

Design the experience to align with visitors' expectations, needs, and interests

The science museum professionals we interviewed repeatedly called out the importance of creating an experience that not only works for the museum but also leads to positive visitor experiences. First and foremost, they cited visitors' desires for social experiences. Participants stated that visitors are less interested in simply viewing screens or using their phones during experiences, as these activities prevent opportunities for group interaction. This finding is consistent with other research (Beale et al., 2022; Komianos, 2022; Shehade & Stylianou-Lambert, 2020) showing that museum visitors sometimes regard immersive digital technologies as *"cold and inhuman"* (Collin-Lachaud & Passebois, 2008) on account of their potential to isolate individuals from others in their group. Instead, visitors prefer experiences that actively invite them to engage with others in meaningful ways—be it other members of their group or museum professionals themselves.

Participants also said that visitors want to experience something unique when they visit a science museum. They believe that digitally immersive exhibits are most effective when they offer visitors experiences that cannot be had anywhere else. One way to achieve that aim, they agreed, is through exhibits that are multisensory, interactive, and self-controlled.

Accessibility and inclusivity were also key priorities for participants. The science museum professionals we spoke with indicated that immersive digital experiences should be accessible to visitors regardless of their age, their abilities/disabilities, and their pre-existing

levels of science content knowledge. They also discussed the need to provide content that does not impose additional costs on visitors (thus ensuring financial accessibility) and that can be provided in multiple languages. Finally, participants said they are seeking immersive digital experiences with low entry barriers so that visitors can immediately begin their interactions with minimal support and direction.

How this applies to *Europa Prime*

Europa Prime was designed with and for neurodivergent students, which is a key asset. As science museums are looking for experiences that are accessible to a broad range of individuals, the fact that *Europa Prime* reflects the needs and interests of a neurodivergent audience would be considered a strength. In fact, at least one professional specifically called out overstimulation as a challenge that many individuals on the autism spectrum face in regards to digital immersive experiences.

User testing of *Europa Prime* (Barchas-Lichtenstein, et al., 2024) did, however, point to a number of other considerations that would need to be addressed for implementation in science museums. As currently designed, *Europa Prime* requires that users receive support and training as they engage with the experience, especially if they are new to VR technologies. User testing also revealed that motion sickness was a barrier for some users. These challenges would need to be addressed, potentially by reformatting the experience to work in a different platform beyond VR.

Ensure that experiences support effective, efficient museum operations

Given both the high costs of digital immersive experiences and the budgetary constraints many science museums are confronting, the professionals we spoke with indicated that they are very deliberate in their decisions about adopting a given product. Wary of digital technologies whose chief value is novelty, they are generally unwilling to invest in digital immersive experiences with uncertain staying power—especially if these cannot be leased to other museums in ways that allow for seamless, cost-free adaptation. Along with this, participants were generally unwilling to commit their limited financial resources to digital immersive experiences that easily break down or that cannot be repaired without the assistance of costly third-party technicians.

Staffing demands and throughput are also key operational concerns for the science museum professionals we interviewed. Many digitally immersive exhibits, they noted, cannot be run unless additional staff are hired to collect tickets, provide instructions and guidance to visitors, and clean equipment. Because of this, participants regarded some of these exhibits as cost prohibitive—especially when they do not accommodate enough visitors to generate sufficient revenue for paying additional staff. From a financial standpoint, participants regarded VR as especially burdensome, as many VR exhibits do not accommodate large groups and require multiple staff members to be present at all times. Participants were also concerned about low throughput from a visitor satisfaction perspective and wanted to ensure that visitors did not feel they were missing out on a key experience during their visit.

How this applies to *Europa Prime*

Current implementations of VR in science museums tend to play into many of the operational constraints that hinder the adoption of immersive digital technologies. The professionals we interviewed specifically called out the high costs of maintaining and staffing VR experiences and raised concerns about throughput. Adapting *Europa Prime*'s content to fit other immersive digital technology platforms beyond VR may lead to a higher rate of adoption of the experience by science museums. One potential consideration is projection mapping, which was mentioned favorably by many participants.

Conclusion

Immersive digital technologies offer science museums a way to expand their offerings and engage audiences through inspiring, interactive, thought-provoking learning experiences. Fully aware of this, the science museum professionals we spoke with are continually assessing the extent to which these technologies can help them create more impactful and joyful visitor experiences. However, while willing to experiment with new technologies as they emerge on the market, participants indicated that they are unlikely to adopt these technologies unless they align with their museums' learning goals, the interests of their visitors, and their own operational needs. Instead of pursuing *"technology for technology's sake,"* they only consider this in the context of specific content they want to convey. Their aim is not to make technology the focal point of their exhibits but to leverage this as a tool to facilitate STEM learning, provide their audiences with unique and accessible social experiences, and support efficient museum operations.

By aligning their educational experiences with these considerations, developers seeking to create digitally immersive exhibits can increase the likelihood that their products will be adopted and implemented in science museums. First and foremost, developers should leverage the power of immersive digital technologies to promote science learning through awe-inspiring, interactive, emotionally engaging experiences. Along with this, developers should prioritize the creation of exhibits that promote meaningful social interactions between visitors and that offer them experiences they cannot have elsewhere. These experiences must also be accessible to visitors of varying ages, abilities, and cultural backgrounds. Finally, on a practical level, these experiences should take into account the operational realities museums live in, ensuring that implementation requires neither additional staffing nor an increased budget. From an operational standpoint, ensuring sufficient throughput is also important so that the large numbers of visitors attending science museums can participate in the experience during their visit.

By attending to these factors, developers can create digitally immersive experiences that successfully engage new audiences in science learning for generations to come.

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