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Museum Leadership for Engaging, Equitable Education: The Transformative Potential of Digitized Collections for Authentic Learning Experiences

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Abstract Museums are local-to-global organizations operating in a digitized, distributed, and diverse 21st century world. Museums leaders face significant challenges in achieving broader relevance, meaningful engagement, and equitable outreach. This article examines the transformative potential of digitized collections to increase public engagement and enhance authentic educational efforts of museums, with specific emphasis on visual media as a key resource to achieve these outcomes. Using digitized collections to broaden learning opportunities and support a wide range of users will require museum leaders to engage in strategic digitization efforts—supplementing research images, making conscious decisions about meeting educational needs when setting digitization policies, and investing in meaningful outreach with digitized collections. Educational opportunities are contextualized with brief case studies of authentic investigations for middle school learners using digitized objects from a natural history museum. Three lessons learned during development and evaluation are described and implications for museum leaders are discussed.

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INTRODUCTION

Today's museums are local-to-global organizations operating in a digitized, distributed, and diverse 21st century world. Even as public trust has eroded in government and media organizations, museums remain trusted bellwethers of credible information and repeatedly are classified as organizations worthy of this distinction (Dilenschneider, 2019). But museums face a significant challenge in leveraging their credibility and trust into broader relevance, meaningful public engagement, and more equitable outreach that creates expanded opportunities for learning with museum collections. Achieving these goals requires that museums actively work to reduce educational inequities, proactively revising traditional outreach approaches in order to develop learning experiences that create new opportunities for participation (Feinstein, 2017). Progress toward this vision is within reach, but museum leaders must—urgently and fully—embrace an expanding digital world where digitization advances public education in addition to research. For 21st century museums, digitized collections that are designed for meaningful public learning—through integrated, in-depth, and well-supported educational experiences—will be foundational to increasing relevance and impact. But it is critical to recognize that these outcomes will not be passive consequences that occur automatically when collections are digitized and put online. Museum leaders will need to be intentional and strategic advocates of an expansive vision of digitized collections, setting policies, procedures, and targeted efforts that build foundations for future success.

Collections Digitization as the Foundation for Modern Museum Impact

Digitization of museum collections has been a major initiative at modern museums for quite some time, with some organizations—including the Smithsonian—engaging in digitization efforts as early as the 1970s (Clough, 2013; Primary Research Group, 2015). Digitization is defined "broadly to include transcription into electronic format of various types of data associated with specimens, the capture of digital images of specimens, and the georeferencing of specimen-collection localities" (Network Integrated Biocollections Alliance, 2010, p. 3). Digitization of expansive collections is a daunting task; given limited resources, museums must establish priorities for digitization—typically developed based upon preservation needs, rarity, or (research) importance (Hedrick et al., 2020). Efforts to digitize collections rapidly and at scale have led to new methods for automatizing digitization workflows (Allan et al., 2019; Hudson et al., 2015), creating low-cost pipelines for 3D digitization of specimens (Medina et al., 2020), using rapid conveyor systems for automatized digitization (Sweeney et al., 2018), and training machine learning models on massive quantities of digitized data in collections repositories (Echevarría Ramos & Hulshof, 2019). However, the purpose of this paper is not to review digitization methods or to propose new digitization techniques. Rather, our purpose is to engage museum leaders in reflecting on the digitization priorities that will be needed for effective public impact of digitized collections, with specific focus on the resources needed to support in-depth educational experiences. Collections digitization for education should not be an afterthought—explored after other needs have been addressed. Rather, education needs should be considered and prioritized as a core component of digitization policies and approaches.

For digitization to have optimal impact as a critical resource that strengthens outreach and participation via meaningful learning, policies and procedures must prioritize the inclusion of high-quality, robust, and (when possible) cutting-edge visual media. Research has established that visual media play a unique role in learning: working with visual materials increases individuals' depth of cognitive processing during a learning opportunity, leading both to better long-term memory and enhanced understanding (Butcher, 2014; Butcher & Davies, 2015). Learners frequently exposed to multimedia self-report greater involvement, focus, and equity in the learning environment (Chipangura & Aldridge, 2017). Visual media also support object-based learning, which serves to enhance learning opportunities and motivate learners through a natural interest in (and emotional reactions to) real world objects (Dierking, 2002). Museum collections provide unique opportunities to support learning with compelling objects that have inherent scientific or cultural importance. The arguments in this article and the implications for museum leadership are applicable to all museums where research and scholarship can be centered on visual media of collections, including art museums and historical museums. However, we will contextualize our arguments by offering specific examples from our own museum context: museums of natural history. Digitization for education may seem like an abstract idea or one that already is served by existing practices. But in reality, current practice often falls far short of what is needed.

Visual media in digitized collections

Image capture frequently is mentioned as a key aspect of digitization efforts, with inclusion of 2D specimen images sometimes discussed as a standard and assumed component of "Digitization 1.0" efforts, particularly in natural history museums (Hedrick et al., 2020). But, in fact, relatively few of the amassed digital records from natural history collections currently contain visual media. By visual media, we refer to the subset of media derived from collections objects and specimens that are primarily visual in nature, including images, models, three-dimensional (3D) visualizations, scans, etc. These media are not to be confused with other data in specimen records—measurements, observations, genetic sequences, metadata, etc.—that are not primarily visual. At the time this article was written, iDigBio (https://www.idigbio.org/) boasted a total of 121,428,342 specimen records and 31,871,262 media records—an impressive overall number of digitized records, but the large discrepancy between these two numbers is potentially limiting for outreach and education.

One might argue that 31 million records with media seems sufficient for public learning, but the reality is that a lack of sufficient imaging during collections digitization limits the depth and breadth of possible outreach activities. For example, searching iDigBio for "Mutillidae" (the focus of a current middle-school research investigation being developed by the authors) retrieves a total of 49,301 records, but only 454 records are returned when the same search is refined to include only records that include media. Of the 454 records containing media, just 231 records (<0.005% of the total) also include geographic locality and collection date. Within this small set, many media consist of only a single image (i.e., a single viewpoint) of the specimen and the resolution of the image(s) varies. These observations are not a criticism of iDigBio, which is an enormous undertaking with great potential value. However, these findings point to a potential disconnect between what organizations—even those contributing to high-quality and much-needed digitization networks—currently prioritize during collections

digitization and what public audiences may want or need for effective engagement through education and outreach programs. For robust outreach and meaningful learning activities, digitization efforts should (whenever possible) include high-quality visuals taken from multiple viewpoints. We recognize that it is not practical for every object in every collection to include such robust visual media, but this is not an all-or-nothing proposition. Collections and objects with critical metadata (e.g., location, date) and with some level of spatial and temporal diversity are good places to start.

We should be clear that iDigBio publishes helpful standards for image digitization online (iDigBio, 2020) that, when followed, can result in the creation of visual media from collections specimens that enhance and support meaningful use (Echevarría Ramos & Hulshof, 2019). So why might high-quality, scaled images from varied viewpoints be included so infrequently in existing digitization efforts? Beyond potential concerns about cost (as discussed below), museums also may not recognize the necessity of high-quality and varied visual media in supporting broad outreach and educational usage. For museums where images are central to their holdings (particularly art museums), there also have been considerable concerns about how and when the public can access images of the digitized collections. In a digital world, control over content is difficult to guarantee or maintain, suggesting that it may be time to update museum expectations to include true public engagement—which includes not only access but potential adaptation or posting of art images by public users (Fouseki & Vacharopoulou, 2013; Michel, 2019). This does not diminish museums' roles as stewards of scientific and cultural heritage (museums can and should have policies on commercial and non-commercial usage), but it does require that museums become comfortable with the probability that broad and diverse public engagement will look different from visitor programs and experiences of the past. Particularly contentious is access to and potential adaptation of visual media, with some museum leaders —including the head of Web at the British Museum—suggesting that digitization efforts should be focused on text content rather than images in an attempt to reach broader audiences (Fouseki & Vacharopoulou, 2013). Our experience in connecting to public and educational contexts has led us to a contrary view: that visual media are essential for creating public engagement and enhancing understanding in formal and informal contexts. This observation is supported by research in learning: studies repeatedly have found that visual content increases depth of learning processes and quality of learning outcomes (Butcher, 2014; Mayer, 2001); when given a choice, more than 98% of individuals rate materials that include visual content as more helpful to their learning than text information (Serra & Dunlosky, 2010). There is no question that digitized (metadata) records without associated visual media have value for scientific research. But visual media is—and will continue to be—the fundamental form of a digitized record that has the potential to increase public engagement and enhance educational efforts.

There are, without question, costs associated with producing digitization records containing visual media. Three cost areas include technology access (including hardware and software) necessary to capture visual media, personnel costs associated with producing, uploading, and maintaining digitized collections, and storage costs (including data backups) for digital assets. Added costs may seem daunting to museum leaders, who face already-strained budgets. However, some costs have declined rapidly in recent years. Advances in technology and increased availability of equipment have greatly

increased opportunities for museums to acquire equipment at reduced cost, potentially via targeted donor gifts. Reduced costs also have resulted in significant acquisition of digitization technologies by libraries and institutions of higher learning, creating exponential growth in meaningful collaboration opportunities. Prices for digital storage have dropped significantly in recent years, with continued projections of a 25–40% decline in data storage costs annually (Harris, 2019). As a result, data storage —even for visual media—is no longer is the cost prohibitive, limiting factor that it had been in the past. The largest, continuing cost associated with collections digitization are personnel costs, which may require rethinking and retooling skill sets of museum workforces—both when selecting new hires and when planning professional development for current staff. Modern museum staff will need digital skill sets, and museum leaders can support their growth and development in these areas.

Museum leaders must consider all digitization costs as part of a larger (and complex) cost-benefit analysis. Recent research on museum business models (using case studies of two art museums: Tate Modern and Pompidou Centre) has found that investments in digitization offer museums new opportunities to diversify and expand self-generated income. That is, digitization can drive business model innovations, such as selling online memberships and offering digital sponsorship opportunities (Alshawaaf & Lee, 2021). The same study found that rich digital content creates value and excitement for customers that can translate into expanded merchandise sales. Beyond direct income, our own museum has found that digitized collections enhance the ability to experiment with exhibit space, providing substantially more flexibility than physical objects and resulting in new opportunities for creative display. Museum-specific research has established that technology-mediated learning—when perceived as intuitive and interactive—increases cognitive engagement and emotional reactions of visitors (Pallud, 2017). Targeted educational programs that use digitized content increase the local relevance of museums, creating strong justification for public investment and clear foundations for funding proposals.

Leveraging investments in digitization and visual media

When the results of a cost-benefit analysis favor digitization (as has been the conclusion for many museums with digitization initiatives), significant questions remain to be answered about how to prioritize digitization of varied collections, what information to digitize as part of object records, how to balance speed and completeness when engaged in massive digitization, and when/how public access is allowed. Museum leaders will continue to struggle with these questions and it may be tempting to de-emphasize the inclusion of visual media in order to make more rapid progress on large-scale data digitization and access. Adding media does require (relatively inexpensive) additional data storage capacity, but also increased labor. This is where expanded digital skill sets of museum staff can greatly enhance capacity in cost-effective ways, allowing production of visual media for digitized collections to become part of museum roles.

Digital materials—and visual media in particular—are a woefully underutilized resource to expand the reach of museum materials and create equitable opportunities for learning with collections. But expanding the impact will require more than production and archiving. Leveraging investments in digitization for public engagement requires careful attention to how digitized resources are

stored and made available for multiple users. In particular, connecting broad populations of public learners with digitized collections will require rethinking how resource retrieval is supported by existing digitization networks and portals. Many public users will not understand scientific categorizations or debates (e.g., taxonomic concepts) and may simply want to access specimens by name (Beaman & Cellinese, 2012) or defining characteristics. Researchers in information search and retrieval have been exploring methods for efficient retrieval without specialized terminology for decades (Salton & Buckley, 1990; Sihvonen & Vakkari, 2004; White & Marchionini, 2007), but searches within digitized collections continue to emphasize terminology that is unfamiliar to a majority of public users and novice learners.

As one example, MorphoSource by Duke University (https://www.morphosource.org/) provides access to truly stunning 3D media—including bat crania. However, (at the time of writing) searching the keyword "bat" in MorphoSource returns precisely three results from two species—a potentially disappointing outcome for a public user. In contrast, searching for a specific project title ("Digitizing extant bat diversity") returns 437 specimens with 708 associated 3D media files. MorphoSource's search instructions appear to assume a relatively high level of scientific knowledge, noting ". . .you might be interested in seeing the Museum of Comparative Zoology's holdings of skulls of the genus Alouatta (howler monkeys). In that case, you might type in 'MCZ skull Alouatta'" (https://www.morphosource.org/About/userInfo). While this is good advice for scientists or advanced students of biology, it is a missed opportunity not to consider how search and retrieval can support public users and novice learners. Whereas iDigBio and GBIF return many more resources to a novice user who searches the term "bat" (829,172 and 1,264,992 results respectively), appropriate methods to filtering these huge results lists are likely to be non-intuitive to public users (e.g., iDigBio provides options for hierarchical filtering by kingdom, phylum, class, order, family, scientific name, etc.). Even in more formal educational contexts, current databases are difficult for teachers or students to use, with search interfaces that are most appropriate for collections experts or taxonomists (Thiers et al., 2019). There may be significant opportunities to utilize new forms of search and retrieval, particularly all-visual search mechanisms (e.g., searching collections by color, pattern; Benoît & Agarwal, 2012). Digitization networks are a key resources to help individual museums achieve sustainability of their digitized collections—shared repositories enhance broad usability, ensuring consistent formatting, available bandwidth, and large-scale availability. But as museum leaders work toward digitization efforts that include the digital media needed for expanded public reach and engagement, they will be critical advocates in helping digitization networks prioritize the development of new, intuitive methods for public search and access. Museum leaders who prioritize visual media not only create the foundations necessary to achieve these new forms of public access, they also set the stage for new forms of outreach that advance more equitable education.

Museum Movement Toward Equitable Education

Museums in the modern era increasingly have emphasized growth toward equity and diversity in visitor populations, access to collections, and outreach efforts. These core values are reflected in

published ethics guidelines for museums which argue that a museum's programs not only should be "founded on scholarship and marked by intellectual integrity" but also should be "accessible and encourage participation of the widest possible audience consistent with its mission and resources" (American Alliance of Museums, 2000). Implementing programs that achieve this breadth within the museum environment is a significant challenge, particularly since the demographics of visitors to brick and mortar museums have remained unrepresentative of local diversity. Museum visitor logs show inequities both in geographical access and in rates of visitation among traditionally underserved populations. A 2010 study by the American Association of Museums found that although racial/ethnic minorities made up 34% of the national population, they represented only 9% of museums' core visitors (Farrell & Medvedeva, 2010). Further, rural audiences may have few opportunities to access museums, particularly when geographical challenges are coupled with socioeconomic issues. Online educational programs are not a panacea—they cannot resolve ongoing inequities related to connectivity issues or the digital divide. However, when online access is available, these digitized experiences can create more equitable museum engagement for learners spanning a wide range of ages, locations, prior knowledge, and interests.

Many museums have undertaken significant and sustained efforts to expand their outreach to underrepresented groups and increase the diversity of visitors coming to them. However, when programs are deployed within the museum environment or reflect traditional conceptions of outreach, museums will struggle to move the needle toward more equitable learning opportunities. Digitized collections offer a potential path forward, but this work is about more than online access. It will require museum leaders to explore and experiment with new ways to deeply engage a wide variety of learners. They should consider that equitable learning opportunities will need to be structured for a broad range of individuals to gain new insights and self-direct their learning experiences. But museum leaders set the foundation for this approaches by creating the digitized materials and institutional culture necessary to achieve this vision.

Digital media as foundations for expanded reach and engagement

Research in museums has shown positive impact of objects on learner engagement and satisfying user experiences (Schwan et al., 2014); museum objects evoke strong emotional responses like "gawking in awe" or "recoiling in horror" (Alberti, 2005, p. 571). Visitors' emotional reactions to museum objects are impressive considering that—in most museums—the majority of objects and specimens are available only for viewing. Although museum visitors are drawn to hands-on opportunities with objects (Willcocks, 2008), the need to protect and preserve collections materials into perpetuity is unlikely to change. High-quality, digital media represent unique opportunities for on-demand access to collections materials in formats that facilitate engagement and interaction. When multiple image viewpoints are available, users can explore features that interest them by selecting different views to examine. Users can enlarge or zoom into an image to examine specific features or details—usually with the result that they can observe a digital object more closely than a physical object in the museum environment. This type of in-depth, virtual exploration can augment exploration opportunities in the museum environment. Indeed, research in museums has found that technology-mediated learning—when perceived as intuitive and interactive—increases cognitive engagement and emotional reactions

of visitors (Pallud, 2017). Museum leaders should consider digitization policies that not only prioritize the inclusion of high-quality visual media but that also (whenever possible) facilitate observation and analysis of visual features from multiple views. Using digitized collections to broaden and diversify public access likely will require supplementing the images created for specific research or curatorial initiatives with additional (often holistic) views.

In addition to 2D images, 3D scans are becoming more readily available and have distinct potential advantages for engaging audiences online. When coupled with 3D viewer technology, 3D scans are highly interactive; viewers can rotate the scan, zoom in and out, and even utilize views not available with the physical object (e.g., viewing the interior of a hollow structure). In a study of augmented reality using museum objects, Kyriakou and Hermon (2019) found that nearly 90% of children visiting a museum agreed that the virtual specimens looked real. More than 90% of the children found working with virtual museum objects to be enjoyable and about 70% noted that they wanted the 3D materials on their own mobile devices. In an educational context, 3D materials appear to be especially useful for engaging spatially-gifted students (up to 6% of students of the 56.6 million students in the United States), who are poorly served by conventional instructional materials and—potentially as a result—are more often identified as disruptive and disengaged during traditional learning activities (Lakin & Wai, 2020). Innovative museum materials can serve as a foundation to engage these underserved learners.

Creating 3D scans presents another key opportunity for museums—the ability to print 3D replicas from collections for physical exploration. Available data from museum audiences suggest a strong appetite for such interaction. In a study of 3D prints with adult museum visitors, 93% indicated that being able to handle 3D prints of collections objects would enhance their museum experience (Wilson et al., 2017) and 62% noted that being able to handle the 3D prints would make them visit the museum more often. Including 3D scans in a digitized collection offers the potential not only for online interactions, but also for tangible interactions with collections outside the museum when 3D printing is employed. These technologies have the potential to engage a range of learners in museum-based learning, including underserved populations such as autistic learners, who particularly benefit from inquiry-based, hands-on activities in the museum environment (Deng, 2017).

Digitized Collections for Authentic Education

For nearly two decades there has been a recognition and growing concern that as museums focus on digitization and online posting of their collections, they will struggle to achieve meaningful use of digital collections in ways that embody their mission (Müller, 2002). However, concerns about depth of engagement are not unique to the digital sphere; there are questions as to the depth with which museum visitors engage with displayed collections during in-person experiences, as some studies have shown that visitors rarely spend more than 10 seconds viewing a single item in person (Krukar & Dalton, 2020). Deep, meaningful learning requires interesting questions, the ability to analyze collections related to those questions, and the generation of new insights, inferences, or conclusions.

There is clear value in the informal, interest-driven approach deployed by visitors to a museum and digital experiences are not intended to replace in-person museum visits. But realizing the full educational potential of museum collections will require that museums also are open to (and invest in) creating fully-supported opportunities for deep, meaningful learning with digitized collections. Even in classroom environments (where materials and processes are more clearly supported), free choice and unstructured inquiry typically do not lead learners to delve into materials with sufficient depth to gain new insights. An authentic, shared question is needed to spur meaningful, collaborative learning (Vartiainen & Enkenberg, 2013). Authentic questions (and investigations) should reflect the nature of research in the field—specifically, questions that are meaningful to the domain of study, open to new analysis and discussion, and can be addressed using research activities that align to professional approaches. Digitized collections can serve as the foundation for investigations driven by a meaningful research question (in science, art, archaeology, etc.) that can be answered by analysis of real (but virtual) collections specimens or objects.

The argument that visual media of digitized collections provide a unique opportunity for meaningful learning experiences is rooted in a robust principle from learning science: the multimedia principle (Butcher, 2014; Mayer, 2001). The multimedia principle is drawn from decades of research examining learning outcomes and processes associated with instructional materials that include visual content (i.e., multimedia) vs. text alone. Research shows that multimedia materials significantly improve learner outcomes, including factual memory for learned information as well as the ability to transfer and apply learned content to new situations (for a summary, see Butcher, 2014). Unsurprisingly, learners' judgements almost universally reflect the belief that they learn better when visual content is provided in learning materials (Serra & Dunlosky, 2010). During our own development of paleontology investigations with digitized collections for middle school students, we observed sustained and compelling student engagement with visual media. Students self-reported digitized fossils to be highly engaging and students' most frequent suggestion for improving the investigations (after "nothing") was the addition of more digitized fossils (Butcher et al., 2017). Surveyed teachers unanimously reported that their students were interested in the investigations and that learning outcomes were worth invested classroom time (Butcher et al., 2017); educators highly valued online investigations with digitized collections as a unique way to engage every student in realistic, meaningful, and interesting research.

Investigations surrounding digitized collections objects/specimens are a form of object-based learning. Object-based learning has transformative potential for education for several reasons, not the least of which is that objects have inherent motivation, expectations, and interest (Dierking, 2002). Experiences with objects serve as the basis for personal reflection and communication with others (Paris & Hapgood, 2002) and objects can be more easily tied to prior knowledge (Dierking, 2002). Facilitating optimal learning outcomes from object-based experiences requires learning opportunities to be reinforced and to recur over time (Dierking, 2002), but loans of authentic materials from museums tend to be limited in scope and duration. In practice, they also are infrequent; specimen loans from the Museum of Southwestern Biology Division of Mammals showed that only 17% of loans fell into the category of non-research, including loans for exhibition as well as education at

all levels (McLean et al., 2016). Further, museums' physical educational collections—real objects available for hands-on learning—often are composed of materials that are not well-suited to permanent collections. Objects may be degraded, lacking metadata, be outside the scope of collections and curatorial expertise, or be haphazardly grouped (Macfarlan, 2001). Specimens may be placed in jars or in protective casings, severely limiting potential for observation and measurement activities. While museums should be applauded for creating hands-on educational resources, it is time for digitized collections to do what traditional educational collections cannot: allow fully-interactive exploration and analysis of a museum's high-value, permanent collections. Opportunities for investigation of objects and specimens from collections with demonstrated scientific or cultural value allow students to pursue real questions, as intended by reformed education approaches emphasizing that learning activities should resemble professional processes (as appropriate for learners' cognitive and developmental levels).

In the case of science education, Next Generation Science Standards (NGSS) incorporate a three-dimensional (3D) approach to science learning that focuses not only on helping students understand disciplinary core ideas and crosscutting concepts of science, but also emphasizes a practice-based approach to learning about scientific phenomena. NGSS notes that students should learn to articulate and apply the research practices that scientists use to conduct meaningful investigations about phenomena in the natural world. A key question is how to develop science investigations for young learners that are aligned with NGSS and are highly engaging and relevant, scientifically authentic and rigorous, and scalable to varied contexts. Although one approach has been to download scientific datasets for student analysis, existing datasets are abstract and skip learners past essential activities that occur before analysis (e.g., gathering relevant data in a form conducive to current and future analyses). Modern collections-based research—using objects from museum collections to answer cutting-edge research questions—offers a way to engage broad populations of learners in real investigations with a purpose.

While there has been significant enthusiasm about integrating digitized museum collections into learning contexts (Neely & Langer, 2013), there has been little consensus about the educational levels best served by digitized collections. A number of researchers argue that digitized collections should be used to transform undergraduate education (Cook et al., 2014, 2016), noting that digitized collections offer unprecedented access to big data that was previously limited to established scientists (Lacey et al., 2017). Although digitized collections undoubtedly are appropriate for undergraduate courses, museums can—and should—engage learners at much earlier ages, reaching generalized populations of diverse learners at opportune times to inspire excitement and interest in collections and the research questions that they can address. Indeed, some researchers have noted that specimens, images, and data from digitized collections have educational potential "at all levels and in all venues" (Powers et al., 2014). We agree with this sentiment, but we caution museum leaders that targeting multiple educational levels will require a strategic analysis of whether current digitization policies are producing the virtual collections materials that are necessary to achieve this vision.

Museum leaders can enhance breadth and equity in outreach by endorsing a movement toward developing well-supported, meaningful learning experiences, particularly collections-based investigations with digitized objects at elementary and middle school levels so that students are engaged with museum collections before career and academic interests begin to crystallize. It is not enough to provide online access and assume teachers will have the knowledge and skills necessary to utilize digitized collections in meaningful ways. Teachers typically have had limited opportunities to participate in research projects, with the result that they lack expertise in developing realistic research activities using collections objects/specimens (Feldman et al., 2013). Museums leaders can help bridge this gap by advocating education efforts in their strategic initiatives and embracing a culture of innovation, experimentation, and collaboration in outreach efforts. In the next section, we present a brief case study of the form and approach that online, collections-based investigations can take, using examples of our own museum-based investigations created for middle school classrooms: Research Quest and EPIC Bioscience.

Research Quest and Epic Bioscience: Authentic Investigation of Digitized Objects and Specimens

Research Quest and EPIC Bioscience lie at the intersection of collections digitization and student/teacher needs for authentic, scaffolded, and recurring research experiences that meet NGSS standards. Investigations are interactive and delivered online, addressing a real research question and engaging students in the practices of the field in which the investigation is situated.

Research Quest (researchquest.org) began as an interdisciplinary collaboration between museum educators, paleontologists, learning scientists, and curriculum developers—the initial effort culminated in a set of investigations ("The Mysteries of the Cleveland-Lloyd Dinosaur Quarry") using digitized fossils from the paleontology collection at the Natural History Museum of Utah (NHMU). Museum leadership supported early efforts via a cross-departmental project team (including curators, museum scientists, university faculty, executive and associate directors, a philanthropy director, program directors, and museum staff), who all came to the table to innovate museum-supported learning experiences. A cross-departmental project team meant that individuals from varied roles and perspectives all had a voice in decision-making and developing consensus, allowing early experimentation, reliable (ongoing) buy-in, and the development of an institutional strategy to fund related activities. Initial funding and investment was small: a $100,000 grant that covered personnel costs and modest technical expenses: $2,000 in laser scanning (contracted externally) with resulting 3D models stored on a $50 portable hard drive. Leadership celebrated initial successes, encouraged innovative approaches, developed relationships with national advisors to help inform project strategies, and fostered a culture that emphasized digitization as an institutional value.

In "The Mysteries of the Cleveland-Lloyd Dinosaur Quarry," students examine laser scans of three "mystery" fossils (selected by a paleontologist), beginning with initial observations and hypotheses necessary to reason about what body parts (e.g., claw, jaw) had been found. Students then

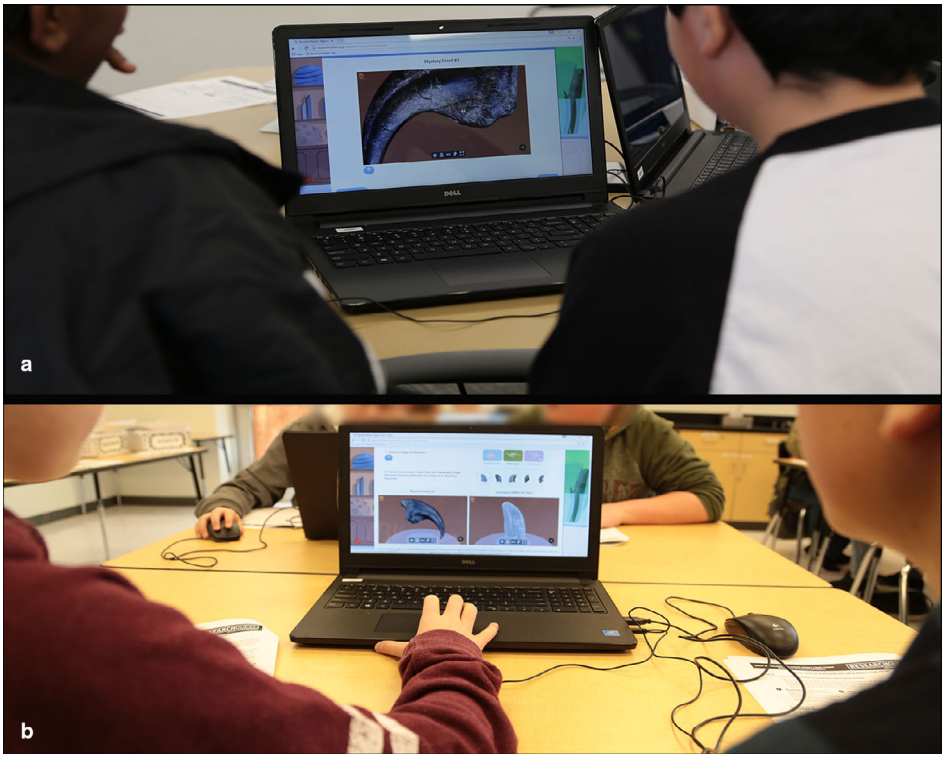

Figure 1. Middle school students use digitized fossils in Research Quest to make initial observations (a) and compare "mystery fossils" to identified fossils from NHMU's paleontology collection (b). [Color figure can be viewed at wileyonlinelibrary.com]

compare their mystery fossils to digitized versions of known fossils from the museum collection in order to identify the dinosaur species (see Figure 1). Research Quest investigations are inquiry-based but structured; students start with rich questions and use targeted collections materials for analysis. Students are supported in documenting their own findings in ways that help them to see patterns of evidence and to develop an evidence-based argument (Butcher et al., 2019). Digitized fossils are embedded in the investigations, so teachers and students can focus on observation, data collection, and analysis rather than trying to find and download relevant collections materials. Videos from a museum paleontologist are included at strategic points to help students compare their thinking to an expert and learn through modeling. Students can (and do) focus on different data during the investigations and come to varied conclusions, leading to productive classroom discourse debating the merits of diverging evidence—not unlike what occurs with practicing scientists. Since its initial launch in 2016, Research Quest has delivered over 165,000 learning experiences (evidenced by student logins) to upper elementary and middle school students. Of the 200+ teachers who have provided feedback, 100% agree or strongly agree that Research Quest investigations provide their students with an opportunity to strengthen critical thinking skills; teachers also report strong participation by typically difficult-to-engage students.

Collaborative relationships forged during Research Quest development coupled with positive feedback from educators and encouragement by museum leaders led the team to seek (and secure) new sources of funding to enhance and expand collections-based learning experiences. One outcome of these efforts is EPIC Bioscience—a project funded by the National Science Foundation (NSF) Discovery Research PreK-12 program. Funding from national research agencies can be particularly high-impact for budget-challenged museums, as matching funds often are not required or (as in the case of the NSF) not allowed. Museum leadership advanced these efforts through administrative support to submit the proposal and strong endorsement of these efforts as a key component of the museum's emphasis on outreach and education. This has allowed continued and varied engagement by multiple museum personnel, including faculty and curators who provide access to collections and scientists who provide inspiration and in-depth thinking needed to create meaningful natural history investigations for learners. EPIC Bioscience is developing a set of specimen-based investigations that will be distributed through the Research Quest website. These NGSS-aligned investigations utilize digitized collections in entomology, vertebrate zoology, and botany to engage students in questions of biodiversity, species loss, and ecosystem change.

A core principle of EPIC Bioscience investigations is that students collect data directly from digitized specimens as the basis for answering research questions. In co-design sessions early in development of the investigations, teachers have been very enthusiastic about students gaining real research experience by working directly with digitized museum collections. In one investigation, students complete visual similarity ratings and take precise measurements of specimens (see Figure 2) from two Müllerian mimicry rings of velvet ants (Mutillidae) and Batesian mimic specimens. Students use resulting data to explore which features (color, pattern, size, etc.) act as predator cues to avoid velvet ant mimics. In another investigation, students gather precise wing measurements (forearm, plus third and fifth digits) of insectivorous bats to determine if bats are aerial or gleaning—they couple these findings with data on jaw strength (drawn from measurements of bat crania) to reason about how changes in ecosystems and insect populations will affect the dietary resources available to bat species.

DISCUSSION

Lessons learned during development of Research Quest and EPIC Bioscience investigations have highlighted three major lessons for museum leadership about using digitized collections for authentic education and outreach. Below, we describe these lessons to help other museum leaders reflect on their own digitization strategies and potential educational impact.

Lesson 1: Prioritize Robust, High-Quality Visual Media in Digitization Policies

Our work has built on a strong and ongoing digitization effort at NHMU; between 2014 and 2016, digitization of herbarium specimens alone increased nearly sevenfold. These efforts have resulted in new policies for the acquisition, creation, and preservation of NHMU digital assets as well

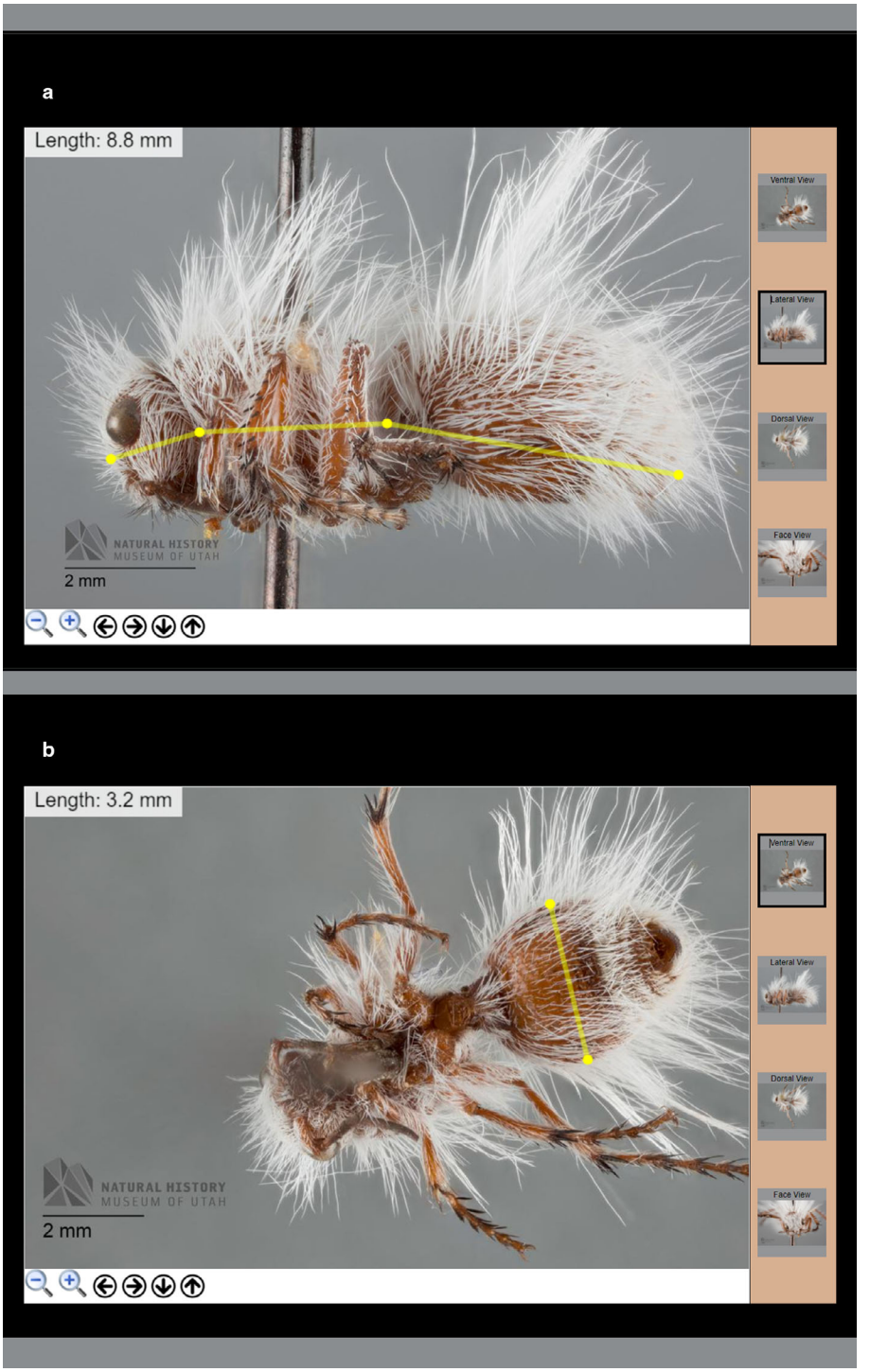

Figure 2. Measuring the overall body length (a) and abdomen width (b) of a *Dasymutilla gloriosa* specimen in an online EPIC Bioscience investigation. [Color figure can be viewed at wileyonlinelibrary.com]

as the recent establishment of digital asset managers that oversee digitization initiatives, including the creation, storage, and maintenance of digitized resources. Nevertheless, each of our investigations has required expansion of the visual media portfolio beyond what was available in existing digitized collections. Research Quest's paleontology investigation was supplemented by high quality laser scans of fossils that were implemented as fully-interactive 3D models online. These models routinely have been noted by educational and public users as the initial feature that drew them into the investigations and made them feel like scientists.

We recognize that most museums (including ours) currently do not have the means to routinely scan collections for 3D modeling; however, even high-quality images from *multiple* views that are created according to iDigBio image protocols (iDigBio, 2020)—including visible color checker and accurate scale—would facilitate development of online educational materials. Our entomology investigation required creating high-quality, scaled 2D images of varied views (e.g., lateral, ventral, dorsal, and proximal views of specimens) to support measurement and observation. When digitized images and views are unavailable, it is a difficult and time-consuming process to identify collections with sufficient specimens for educational analysis. In our own work, development team members have resorted to cell phone snapshots of collections trays to do initial reviews of the breadth and depth of collection specimens, followed by a painstaking process to select specimens needed for the investigation, and (finally) the acquisition of high-quality visual media for selected specimens. Digitized collections that already include multiple instances of high-quality, robust visual media will greatly facilitate meaningful educational use.

Seeing the critical importance of 2D and 3D media for meaningful educational outreach with collections has led NHMU to seek opportunities for strengthening and diversifying the visual media that is produced during digitization, enhancing potential for future public impact as well as scientific discoveries. Museum leaders can start small, exploring available methods for creating expanded sets of visual media in high-impact collections, including the use of volunteers and community partners to implement protocols. As processes and technologies become refined, increasing availability of visual media can fuel expanded outreach. Museum leaders also can voice their support for the development of new, visual-methods for novice-friendly search and retrieval methodologies—such as searching for items similar to a selected "query" image (Benoît & Agarwal, 2012; He et al., 2006) or using machine learning models to index collections based on visual characteristics (Echevarría Ramos & Hulshof, 2019).

Lesson 2: Lead Both Enthusiastic and Reluctant Museum Personnel to Embrace Digitization

Not all museum personnel will embrace digitization of collections quickly or to an equal degree. Whereas some collections managers actively and enthusiastically seek out digitization opportunities, other collections managers have significant concerns about maintaining control over their collections, possible erosion of scientific value resulting from online access, and the types of usage that may occur

online. Ultimately, museum leaders must lead by policy and example. When possible, professional development to develop digital literacies and digitization skills should be prioritized for museum personnel. Museum leaders should clearly communicate the value of digitized collections in supporting the museum's fundamental goals and set clear, written policies outlining expectations for the digitization of existing collections as well as incoming materials. While it may be tempting to seek strong controls over when, how, and why users can access digitized collections, extending reach and serving broad audiences will require that you embrace digitization as a service and a mission to ensure the continued relevance of museums in a digital era. Museum leaders can and should set policies restricting usage of digitized collections to personal, educational, and other non-commercial purposes. But they also should make peace with the reality that there will be some level of uncertainty—both positive and negative—inherent in digital approaches to expanding access. So how can museums ensure that public users work with collections in meaningful ways? Developing authentic educational investigations around digitized collections for learners at all levels is a good start. In this way, the museum draws the public into in-depth thinking and engaged analysis of collections—driving the narrative via authentic learning opportunity, not by limiting access or creating barriers. Creating meaningful, online educational opportunities also allows museums to guide users to digitized collections with appropriate context and reflection, rather than expecting public audiences to create their own context and use cases.

Lesson 3: If You Build It, They Won't Necessarily Come

In order to expand true reach and support meaningful learning with museum collections, it is not enough to digitize collections and make them available online. Even with significant personal interest and motivation, few individuals have the scientific expertise necessary to utilize existing digitization networks in meaningful ways. And although digitized objects and specimens can be tremendous assets for authentic, object-based learning in classrooms, few teachers have the research skill sets necessary to identify relevant questions, retrieve key objects/specimens, facilitate data collection, and guide data analysis. Sparse lesson plans and materials are available for teachers who want to use collections; many of these materials take the form of digital worksheets that lack context for data and fail to engage students in realistic practices. Further, while digitized collections can be an extraordinary educational resource, even online collections that are available to anyone with a fast and reliable internet connection can remain essentially inaccessible without significant scaffolding and guided support.

Learners who are guided in using digitized collections to answer challenging questions gain an appreciation of the role of museums, the importance of research, and the value of examining our shared scientific and cultural collections. During a recent Research Quest session in a Title I classroom, students were asked if they had any questions before the end of class. One student raised her hand, saying that she wanted to thank the team for developing the investigation. "I didn't know any of this stuff," she told us, "I mean, I didn't even know that trees could die." As this student so astutely articulated, an in-depth experience with digitized collections gave her a new way to look at the world

around her. Creating the digitized visual media necessary for these experiences required significant investment, interdisciplinary collaboration, a culture of innovation and iteration, and dedication to finding new sources of funding. But the payoff is the ability to engage a broad range of new young learners in the process of discovery as well as the beauty, value, and meaning of collections.

CONCLUSION

Digitization is a well-known approach to expanding scientific access to museum collections, but museum leaders are doing themselves—and the public—a significant disservice if they set digitization policies and priorities that do not bring educational needs and priorities to the table. While it may be tempting to prioritize large-scale digitization using automatic methods in the near term, a narrow focus on speed and scale will minimize potential impacts of museums and their collections for learners and public users. Museum leaders who decline to consider needs associated with educational outreach—particularly the need to create multiple instances of high-quality, robust visual media—as they make digitization decisions may find themselves behind the curve as museums seek expanded reach and increased relevance in the coming years. Without public, educational considerations integrated early in digitization strategies and policies, museums may find a bifurcation in their processes —with digitized collections for research and digitized educational collections proceeding on different paths. If such an institutional divergence occurs, it will be difficult—if not impossible—to merge them back together. Collections managers may question the efficiency of repeating digitization efforts or changing procedures when previous (research-focused) digitization efforts prove insufficient to develop meaningful learning experiences. As a result, digitized education collections may become vulnerable to the same limitations suffered by their physical counterparts: compilations of disjoint specimens and limited media that fail to reflect the true breadth, depth, and meaning of museum collections.

We recognize that generating high-quality visual media, with both standardized formats and multiple viewpoints, will require museum leaders to make significant financial and institutional commitments, particularly with regard staff time and training. Museum leaders may not be able to commit financial resources to all collections in the near future. However, museum leaders should be clear and cognizant of the digitization approaches that will facilitate public and educational access and they must strategically plan to achieve these approaches. Success will require fostering shared institutional values surrounding digitization, supporting professional development related to digital literacy and technical skills, embracing a culture of innovation and experimentation, and encouraging creative funding initiatives. Solutions will not be easy, but museum leaders who prioritize public and educational needs alongside research needs when setting digitization policies and identifying strategic investments will reap the benefits of future relevance and broad reach. END

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