XR for Teaching and Learning:

Year 2 of the EDUCAUSE/HP Campus of the Future Project

Contents

Learn More

Access additional materials on the EDUCAUSE/HP XP research hub at https://www.educause.edu/hp-xr-2.

Author

Jeffrey Pomerantz, Associate Professor of Practice, School of Library and Information Science, Simmons College

Citation

Pomerantz, Jeffrey. *XR for Teaching and Learning: Year 2 of the EDUCAUSE/HP Campus of the Future Project.* ECAR research report. Louisville, CO: EDUCAUSE, October 2019.

EDUCAUSE is a nonprofit association and the foremost community of IT leaders and professionals committed to advancing higher education. EDUCAUSE programs and services are focused on analysis, advocacy, community building, professional development, and knowledge creation because IT plays a transformative role in higher education. EDUCAUSE supports those who lead, manage, and use information technology through a comprehensive range of resources and activities. For more information, visit https://www.educause.edu.

HP Inc. creates technology that makes life better for everyone, everywhere—every person, every organization, and every community around the globe. For higher education, HP combines instructional innovation, applied research, 3D technologies, and advanced information security to empower the Campus of the Future. Learn more at http://www.hp.com.

Executive Summary

For the second year, EDUCAUSE and HP have partnered to study extended reality (XR) in higher education. The HP Campus of the Future is an initiative to promote the institutional adoption of cutting-edge technologies for research and for teaching and learning. EDUCAUSE supports institutions in their efforts to promote student success and identify those technologies that can best support that success.

This report is the result of ongoing collaboration between HP and EDUCAUSE. In 2018, EDUCAUSE published the *Learning in Three Dimensions* report, which explored the then-current state of the art in the use of XR technologies in higher education. This report expands on the findings of that original report. This study asked the research question: What factors influence the effectiveness of XR technologies for achieving various learning goals?

This study found that XR technology is especially effective for supporting skills-based and competency-based teaching and learning. By expanding the range of activities through which a learner can gain hands-on experience, and by enabling the creation of realistic and high-fidelity simulations, XR expands the range of topics that can be learned as skills, rather than as abstract knowledge. This study also found that XR, even where its pedagogical benefits are clear, must still fit into existing curricula and instructional methods. This report presents use cases of XR for teaching and learning as examples, so that institutions of higher education that have not yet deployed XR technology may see how they might start.

Key Findings

- **XR technologies are being used to achieve learning goals across domains.** Whether we are talking about Bloom and colleagues' original trio of educational activity domains—the cognitive (knowledge), psychomotor (skills), and affective (attitudes)—or the revised quartet—factual, conceptual, procedural, and metacognitive—we find that XR technologies contribute to learning gains and produce changes in all domains, though not necessarily all equally.
- **Effective pedagogical uses of XR technologies fall into one of three large categories:** (1) Supporting skills-based and competency-based teaching and learning, such as nursing education, where students gain practice by repeating tasks. (2) Expanding the range of activities with which a learner can gain hands-on experience—for example, by enabling the user to interact with electrons and electromagnetic fields. In this way, XR enables some subjects traditionally taught as abstract knowledge, using flat media such as illustrations or videos, to be taught as skills-based. (3) Experimenting by providing new functionality and enabling new forms of interaction. For example, by using simulations of materials or tools not easily available in the physical world, learners can explore the bounds of what is possible in both their discipline and with the XR technology itself.
- **Integration of XR into curricula faces two major challenges: time and skills.** Students need sufficient time to engage deeply with the technology and with the problem-solving enabled by it. But engaging with XR technology requires that students possess some technical skills, and gaining these skills also takes time. A single academic term may not be sufficient for students to both scale the learning curve of XR technology and also cover the subject matter of the course. Institutional support is needed to ensure that students have the time to gain the skills necessary for effective pedagogical use of XR.
- **The adoption of XR in teaching has two major requirements: the technology must fit into instructors' existing practices, and the cost cannot be significantly higher than that of the alternatives already in use.** First, many disciplines have existing accreditation standards, curricula, and even instructional methods, and the use of XR hardware or applications must fit into such existing ways of doing things. Second, cost might be calculated not simply in terms of money but also in terms of the time required to scale the learning curve, or however the instructor perceives cost.

- **The effectiveness of XR technologies for achieving learning goals is influenced by several factors: fidelity, ease of use, novelty, time-on-task, and the spirit of experimentation.** Fidelity: The more realistic an XR simulation is, and the more it supports the "embodiment" of the user, the more valuable it is as a teaching tool, particularly for skills-based learning. Ease of use: An XR technology must be easy to use for both the instructor and the student. This is partially achieved through increasing standardization of interfaces and functionality. Novelty: XR technology must enable pedagogy that is not available through existing instructional methods. Time-on-task: Like other technologies for blended learning, XR promotes increased engagement for students interacting with educational materials. Spirit of experimentation: Like other developing technologies, XR promotes self-directed learning. But this requires that instructors and the institution as a whole provide students with the freedom, flexibility, and resources to engage deeply with the technology.

Introduction

Extended reality's time has come in higher education. Hardly a week goes by that doesn't see an article in the higher education press about the use of XR in teaching and learning. HP launched the Campus of the Future project to facilitate the adoption and integration of XR into higher education pedagogy; EDUCAUSE is conducting the current research to identify good practices and to promote student success.

This report is the result of this ongoing collaboration between HP and EDUCAUSE. The 2018 *Learning in Three Dimensions* report was an exploratory evaluation of XR technologies in higher education. This report builds on that work. The study reported here was a multiple case study, informed by interviews with 36 individuals at 17 institutions across the United States, about their uses of XR in their teaching and research. (See appendix B for more detail on the methodology.) This study identified types of learning goals that are effectively supported by XR technology, as well as methods for integrating XR into pedagogy to support those learning goals.

Project Description

Background

HP first announced its Campus of the Future project at the EDUCAUSE 2017 Annual Conference, describing it as an effort "to meet the growing challenges of higher education" and "to improve student success, mitigate risk, increase accessibility and enhance teaching, learning and research."[1] An important part of the project was, and still is, to introduce immersive computing to institutions of higher education and to conduct research about that technology. Throughout the project, the hardware has been provided by HP, while the research has been conducted by EDUCAUSE.

Phase 1 of the project spanned the 2017–18 academic year and culminated in the *Learning in Three Dimensions* report. The evaluation questions for that study were:

- What educational activities lend themselves to the use of XR technologies?
- What are the most effective XR technologies for various learning goals?[2]

In brief, the answer to the first question is *experiential learning*; the answer to the second depends on the learning goal. Further, the *Learning in Three Dimensions* report identified several XR technologies that are effective for meeting specific learning goals, along with the mechanisms by which those technologies can do so, as well as the hurdles that institutions of higher education confronted in implementing XR technology. These were the starting points for phase 2 of the HP Campus of the Future project, which spanned the 2018–19 academic year.

This Project

The research question for this project was:

- What factors influence the effectiveness of XR technologies for achieving various learning goals?

This question is more specific than those in the first phase of the study and reflects an effort to unpack the findings in the earlier report. This project explored not just what XR technologies are useful for but also how and why they are so, as well as how the use of XR technologies changes teaching and learning.

As with any rapidly changing technology and marketplace, the terminology around XR technologies is highly fluid. See appendix A for a discussion of this terminology.

Much of the published research on XR for education consists of studies of single courses or projects in which XR technology was deployed or meta-analyses that look across these studies.[3] That is not a criticism of the published research: studies of new technologies tend to proceed through distinct phases, of which description is a critical first step. XR technology is relatively new to educational settings, and the research is only now beginning to emerge from this first phase. The next phase will no doubt be more systematic—still largely descriptive, but descriptive of how XR technology is being deployed and integrated into institutions' processes and services. This type of publication is already beginning to emerge for the corporate sector, as trade publications start to produce articles on future uses of XR.

This study is an effort to move the published literature on XR technology for education in the same direction, that is, to take a higher-altitude view of how XR technology is being integrated into institutions of higher education, not just in one course or at one institution but systematically. At the same time, part of the purpose of this report is to inform institutions of higher education that have not yet deployed XR technology how they might go about doing so productively. This report therefore relies heavily on examples of XR in teaching and learning at institutions that participated in this study. Your mileage may vary, as they say, but hopefully all readers will be able to find something in these examples that resonates with their institutional context and provides some depth and specificity to the broader research findings.

XR Technologies for Achieving Learning Goals

What factors influence the effectiveness of XR technologies for achieving different learning goals? This is a complicated question because the broader question of what factors influence the effectiveness of *any* technology for learning is complicated. The reason this broader question is difficult to answer is that many factors can influence learning: the instructional technology used, the medium of delivery, the quality of instruction, the temperature in the classroom, the student's socioeconomic status, etc.

The *No Significant Difference Phenomenon* is well known. A body of research spanning decades has shown mixed results in investigating whether student outcomes are improved when education is delivered face-to-face or at a distance. This has sometimes been used as a blanket argument against the use of technology in education,[4] but that misunderstands these findings. Rather, what this research shows is that the effects of the mode of delivery are drowned out by the effects of other variables. Many of these studies show that one variable in particular—the instructional method employed—is one of the most powerful factors, if not *the* most powerful, influencing learning. In other words, instructional method is far more important than the medium of delivery … so much more important, in fact, that the effect of instructional method dwarfs the effect of technology into statistical insignificance.

This may seem like an unexpected admission in a report about educational technology. But if XR is to be used in education, it is important to be realistic about how to use it effectively. Other research has shown that blended learning—that is, enhancing face-to-face teaching and learning with online components—achieves better student outcomes than either face-to-face or online alone.[5] It is this type of blended learning environment in which XR is most useful. If instructional method is one of the most powerful factors influencing learning, it is critical that we understand how XR best fits into those instructional methods. XR holds the potential to be a game changer[6] for pedagogy, but it must be deployed thoughtfully in order to fulfill this potential.

Experiential and Competency-Based Learning

In a 2009 interview, Captain Chesley "Sully" Sullenberger, the "Miracle on the Hudson" pilot who famously landed US Airways Flight 1549 on the Hudson River, credited the frequent and repeated simulations that airline pilots perform for his success with that landing: "One way of looking at this might be that, for 42 years, I've been making small regular deposits in this bank of experience, education, and training. And on January 15, the balance was sufficient so that I could make a very large withdrawal."

"We don't know if this is the future, but it sure looks like it."

—Brant Steen, Bucks County Community College

Landing a commercial airliner on water is not something that one can (or would want to) practice in the physical world even once, let alone repeatedly. In a simulation, however, anything can be practiced again and again. Because of the danger, complexity, and expense of aircraft, flight training was one of the first jobs to make widespread use of simulations,[7] and flight simulators are still widely used for aviation training.

Nursing Education Already Uses Simulations

Like aviation, the nursing profession has long understood the value of simulations for training. The Institute of Medicine's 2000 *To Err Is Human* report[8] argued that professional education across healthcare fields should use simulations whenever possible when creating learning environments, thereby enabling students to practice technical skills and thus reduce medical errors.

Training for nurses is extremely specific. State boards of nursing produce scope and standards of practice regulations that inform the creation of checklists of skills by publishers of nursing education resources. These checklists range from basic skills such as taking a patient's temperature and blood pressure to more complex skills such as how to dress different types of wounds and how to interact with a difficult patient. To become proficient in most of these skills requires a nursing student to perform a specific set of steps in a specific order, reliably and without requiring supervision. This is a different model of education from that of many disciplines, different even from many other professional programs. The law, for example, and even other medical training require students to recall a large corpus of knowledge but not usually to execute it in a fixed sequence. What's more, nurses are often working under time pressure and with incomplete information. They must therefore be able to perform specific skills with speed and precision, sometimes in the face of a rapidly changing situation.

Two forms of simulation are widely used in nursing education: manikins and actors. The reader has probably seen and perhaps even used this sort of manikin, for example, in CPR training. These manikins are versatile in that students can practice a wide range of skills on them. But they are not particularly realistic; often they are not even a complete body, just a head and torso, or just an arm, etc. Standardized patient–actors, on the other hand, are clearly more realistic. But actors must be trained to participate in a medical simulation and must also be paid. Scheduling an actor's time adds complexity to an already complex scheduling problem, as students' and instructors' time must be scheduled as well.

Nursing education is therefore an ideal venue for deploying XR technology. Simulation-based training is already widespread, but there is a clear need for simulations that are higher fidelity than using manikins and less complex and expensive than working with actors.

XR Maintains Existing Student-Learning Outcomes in Nursing Education

Two nursing programs participated in this study: the Morgan State University (MSU) Nursing Program, part of the School of Community Health and Policy, and the Simulation Center in the Columbia University School of Nursing. XR technology had already been deployed at both of these institutions prior to the start of this study. At MSU, the library recently purchased a small number of VR backpack rigs (figure 1) and headsets for a makerspace currently being designed and built within the library. The Emerging Technologies Consortium at Columbia was formed under the university's IT unit in 2017 to help facilitate exploration and adoption of new technologies at Columbia.

Figure 1. The HP VR backpack
Image courtesy of HP Inc.

Both the MSU Nursing Program and the Columbia Simulation Center were just starting to use XR while this study was ongoing. MSU was launching an initiative to educate novice nurses to recognize and respond to early indicators of "clinical deterioration"[9] (the deterioration of a patient's condition just before or just after being admitted to a hospital) using high-fidelity simulations. An extensive and detailed set of criteria for evaluating the specific skills being taught accompany these simulations—for example, that the novice nurse "verbally identifies the signs of clinical deterioration" and should "evaluate the effect of medications and oxygen administration on patient's clinical deterioration."

Columbia was starting XR implementation with a case study. Multiple students from multiple nursing subdisciplines, wearing AR headsets, meet with a standardized patient–actor. Students take a patient history and perform physical assessments, etc.; some information is provided by the patient–actor and some is included in AR overlays. Afterward, students meet as a team to make their diagnosis and decide on a course of action for the simulated patient.

For both the MSU and Columbia simulations, students are evaluated on a specific set of skills, which, importantly, are the same skills that could be evaluated in any type of simulation (such as VR, a computer-based simulation on a screen, or a simulation with an actor or a manikin). Instructors have a rigorous set of predefined criteria for evaluating students' performance of these skills, and these criteria can be used across teaching environments. It is a critical point that the use of an XR simulation does not require a change to student learning outcomes. By not requiring this change—i.e., by maintaining existing student learning outcomes—the cost of adopting XR for instruction is dramatically reduced.

XR Maintains Existing Learning Outcomes in Other Disciplines, Too

Another subject for which XR can increase the realism of the learning environment and remain consistent with preexisting learning outcomes is language learning. There are, of course, several excellent language-learning software applications, and in-person language courses are legion. But the one thing even these cannot provide is immersion, which is a particularly effective method for learning a language. Immersion may not be possible for many students, however, as it requires either travel or the presence of a local language community. VR, though, has been found effective in simulating an immersive language environment.[10] At Syracuse University, for example, a project is under way to use 360-degree video to develop virtual tours of landmarks in countries around the world, in the native languages of those countries. For another example, the Sound Storytelling project under way at Yale University records the sounds of rural life in Indonesia, as a tool to immerse the learner in the Bahasa Indonesia language environment. By simulating realistic language environments, XR can enhance language learning by providing the student with immersion where it might not otherwise be possible.

Still another subject where XR can provide a realistic simulation that is consistent with established learning outcomes is chemistry. As Lori Silverman, director of the Science Learning Institute at Foothill College, amusingly put it: "One of the big problems with chemistry is chemicals." Teaching and learning in chemistry requires a lab, which an institution may have the resources and infrastructure to set up but which is prohibitive and possibly dangerous for a student to attempt at home. It is perfectly feasible, however, for a student to interact with a simulated chemistry lab at home. Indeed, this goes for any subject that requires a lab. Furthermore, a simulated lab is especially useful for courses offered by institutions with a large percentage of commuter students. Many educational institutions make cloud-based software applications available to the campus community, such as a learning management system (LMS), enterprise licenses for statistical analysis packages, or subscription library databases; similarly, a virtual lab would enable members of the campus community to interact remotely with another important campus resource.

XR technology is particularly well suited for fields such as nursing, language learning, and chemistry—fields that require students to gain direct experience but where gaining that direct experience is a challenge because it is dangerous, expensive, complex, or remote. The more realistic and the higher fidelity these simulations of the physical world are, the more valuable they are as learning environments. Yet there are things far more complex than a chemistry lab and far more remote than a Bahasa language community. XR is also useful for simulating things in the physical world that simply cannot be accessed physically.

Making the Abstract Concrete

Not all education is competency-based. Some K–12 and higher education courses seek to convey a body of abstract knowledge. Students are expected to come away from certain courses and programs in possession of knowledge but not necessarily a set of skills. It is of course difficult to separate knowledge from skill: How can an instructor assess a learner's knowledge if not by having her demonstrate it by doing something? In many cases the nature of the subject limits what can be demonstrated. Astrophysics and history, for example, are not subjects in which students can easily demonstrate hands-on skills. For many subjects, the object of study is not accessible, for one reason or another. These subjects have therefore traditionally been taught more or less in the abstract, using illustrations, videos, and perhaps models, but without much direct hands-on experience. And ultimately the assessment of a learner's knowledge in such fields has depended on writing, as on an exam or an essay, and not on demonstrating a skill.

> "We want to drag information literacy out of the 19th century."
>
> *—Seneca Jackson, Morgan State University*

XR Expands What Can Be Learned as Skills

One of the most important educational functions of XR is to dramatically expand the range of activities with which a learner can gain hands-on experience. XR can provide hands-on experience of things that are too small to manipulate with hands, such as cells; too large, such as entire physical environments; or not physical at all, such as electromagnetism. In other words, XR dramatically expands the range of topics that can be learned as skills rather than as abstract knowledge.[11]

Several examples of such topics emerged during this research. Perhaps the most fully developed application for this purpose is Cellverse, under development by the CLEVR project at MIT to teach cell biology. Cellverse is a collaborative educational VR game: the cell in question has a genetic defect, which the VR user must fix from within the simulation. Cellverse requires two users (figure 2), the explorer and the navigator: the explorer wears a VR headset and has a view from inside the simulated cell, while the navigator uses a tablet to access a bird's-eye view from outside the simulated cell. The navigator gathers and organizes data about cells, while the explorer makes observations; the navigator's selection of reference information is informed by the explorer's observations, while the explorer is guided by information provided by the navigator.[12] In other words, the navigator is working with abstract knowledge, while the explorer converts abstract knowledge into action. The "winning condition" of Cellverse is for the explorer and navigator team to work together to select an appropriate therapy to "cure" the cell, thereby demonstrating that both users can recall information about the functions of organelles within the cell, can analyze and make inferences about the relationships between organelles, and can generate hypotheses about how to fix the cell and then execute plans to do so. Cellverse has already been used in a few select classrooms to test the effectiveness of the design.

Figure 2. Students using Cellverse to learn about cellular biology
Image courtesy of the MIT Education Arcade 2018

Another application that makes effective use of the hands-on nature of the XR experience to teach a subject that has traditionally been abstract is the Electrostatic Playground. Also developed at MIT, this is a VR simulation of charged particles. Electromagnetism and electrical engineering are often taught as separate topics—related, of course, but traditionally a student is expected to possess the more abstract knowledge about electromagnetism prior to learning more hands-on engineering topics. But the Electrostatic Playground teaches both at the same time. The user manipulates simulated charged particles and experiences how they react to one another. Knowledge that previously could be gained and assessed only in the abstract can now be experienced and demonstrated as a skill.

Authentic Experiences

The learning outcomes for many STEM disciplines, such as biology and physics, are fairly well defined by grade level, at least within K–12 education. Just as with nursing training, the use of a VR simulation increases the fidelity of the experience but remains consistent with established instructional standards in these fields. Cellverse has been deployed in a few classrooms, and both students and teachers have found that it enables the development of a spatial awareness of the cell environment and the contextualization of the roles of organelles in the cell. This is at least partly due to the fact that Cellverse is designed to be an "authentic" experience—authentic both in the sense that the simulated environment matches current research on cells (and is constantly being updated to remain current) and in the sense that the explorer experiences the physicality of the simulated environment. This physicality is especially noticeable in the Electrostatic Playground, where simulated particles move and interact authentically. What was once possible to present only as drawings on a page or perhaps as a video can now be a hands-on experience.

Biology is a particularly popular subject for XR development, perhaps because many of the objects of study are physical but are too small to see with the naked eye. Beyond those discussed so far, several XR simulations exist, or are under development, for teaching biology-related subjects. The VR-Lab at the Norwegian University of Life Sciences is developing a VR application for a molecular biology course, for example, and Unimersiv, a platform for educational VR content, has a simulation in which the user can explore the protein structures on the surface of cells. There are even some Google Expeditions of cells that are compatible with Google Cardboard, a free smartphone-based VR app designed to work with inexpensive headsets. There is also a long list of VR and AR applications that were not developed specifically to be used as part of a course but nevertheless have some educational potential. One example is the unfortunately named InCell, a racing game for Google Cardboard in which the user is racing against viruses.

One of the most valuable functions of XR is to enable the simulation of aspects of the physical world that are not accessible in any other way. As in anatomy simulations,[13] the more authentic these simulations are, the more valuable they are as learning environments. But what does authentic mean when there is no human experience to compare it to? Any simulation of an organelle or an electron is obviously an abstraction. What's important is for such abstractions to be as realistic as possible: simulated organelles and proteins must interact accurately, and simulated electrons should repel each other with an appropriate amount of force, etc. In other words, even though the simulation gives the user an experience that is impossible in the physical world, that simulation must maintain the impression that it is realistic by adhering to the relevant "rules" of the physical world, rules like gravity and other physical forces. By adhering to these rules, a simulation of the physical world can model things that do not—or do not yet—exist.

Experimentation

All new technology is a learning experience. Even a new tool that performs a familiar task (for example, a new spreadsheet application) requires the user to scale at least a small learning curve. And most new technologies possess at least some new functionalities. The functionality or actions that a technology enables are called *affordances*.[14] Affordances can be obvious—for example, that an office chair affords being sat upon. But affordances may not be obvious; an example might be the same chair being used as a racing vehicle.

XR is similar in some ways to existing technologies, such as film. But XR also possesses functionality that is entirely new, enabling users to perform tasks that are not possible with other tools. XR has new affordances: it is not a film, it is not a game, it is something else entirely. Every once in a while an innovation comes along that changes what is understood to be possible in a medium: the development of cubism in painting, for example, or the invention of the electric guitar for music. But this is relatively rare, as most media are well established and their affordances relatively well understood. XR, on the other hand, is changing what is understood to be possible with technology, as its affordances are still being mapped out. Where we are now with XR is perhaps where musicians were with electric guitars in the 1940s: still perfecting the hardware and exploring its possibilities at the same time.

This process of mapping out the affordances of XR—of exploring the functionality and the limits of what is possible with this new technology—is happening across many fields and is one of the most exciting developments in using XR for teaching and learning.

"This is right on the brink of 'Nobody knows what they're doing!'"

—Amber Bartosh, Syracuse University

XR and the Possibilities of Physical Space

The Interactive Design and Visualization Lab (IDVL) at Syracuse University has been using XR to render architectural designs since before this study began (figure 3). XR offers a higher-fidelity, more realistic tool for rendering architectural designs than more "traditional" architectural tools, such as computer-aided design and drafting (CADD) software or scale "dollhouse" models. Rendering designs in XR enables the user to walk around inside a space and interact with the objects, materials, and soundscapes within it.[15] Building a simulated architectural space makes it possible to collect data about individuals' navigation through and interaction with the space and to rapidly integrate those findings into iterating the design of the space.

Figure 3. A VR simulation of interactive windows, at Syracuse University
Image courtesy of Amber Bartosh, Interactive Design and Visualization Lab at Syracuse University

Although they are lumped together under the umbrella of XR throughout this report, VR and AR are different technologies and therefore provide different affordances. This is especially clear in how they are used in the context of physical spaces. VR enables the simulation of an entire space that may not yet exist; AR, on the other hand, is closely tied to the existing built space: the IKEA Place app, for example, enables users to virtually place scale-accurate 3D furniture in a room using a smartphone. This is similar to other smartphone applications, such as Warby Parker, which enables users to try on virtual eyeglasses. Several stores' apps enable users to try on virtual clothes. These are not complex functions, but the point is that these apps allow users to see things as they *might* be, to experiment prior to making a change to one's environment.

Two other examples of projects closely tied to existing physical environments are choreography projects, one at Barnard College and one at Yale University. Barnard College offers several courses that explore the intersection of technology and the performing arts. In one dance course, students develop a choreographic work that is then "placed" on campus so that it can be seen using a smartphone-based AR app. This is a deliberate exploration of two issues that are currently frontiers in dance: site-specific choreography, or developing a piece for a particular site other than a stage, and choreographing a work that will be viewed on a small screen. In the Beyond Imitation project at Yale, a dancer's sequences are captured as motion-capture data, which is then fed to a machine-learning algorithm that generates completely new dance sequences. These sequences may then be viewed as a simulation before being integrated into a new choreographic work by the dancer herself. This sort of computer-generated choreography provides material for the dancer, of course, but in doing so enables exploration of both the nature of artistic collaboration and the "language" of dance.[16]

The Journey Is the Destination

The Beyond Imitation project is one of several under the umbrella of Yale University's Blended Reality project, which, as of this writing, is in its third year. The Blended Reality project continues to experiment with XR technology, for example through the ongoing development of the Clamshell Controller, a universal controller that can take output data from any sensor as input and then input that data into an XR simulation. For input, the Clamshell Controller can use data from existing sensors, such as force pads, light sensors, or accelerometers. But the goal is for the controller to use data from any type of sensor, even one-off custom-built sensors, thereby enabling developers and users to bring entirely new types of data into simulations.[17]

By experimenting with XR hardware or functionality—or both—the projects discussed in this section are deliberately innovating in their respective arenas. These projects are not only pushing the boundaries of their disciplines, they are also pushing the boundaries of our understanding of the capabilities and affordances of XR itself.

As previously discussed, there are many domains in which XR can fit into existing pedagogy while remaining consistent with established learning outcomes. But sometimes experimentation is the point. In the Syracuse

"XR technology is a way to increase the scale of our capabilities."

—Justin Berry, Yale University

University School of Architecture, for example, students in a special-topics course called Mediated Environments did some original development in the XR development platform Unity to create an immersive visualization of environmental data—something none of these students had done before and which is in fact a new method for visualizing environments in the field of architecture at large. In a course at Syracuse called VR Storytelling, in the Newhouse School of Public Communications, students developed a VR experience relevant to their field of study—again, a new experience for these students and new to their field of study as well. To lower the bar to XR development for others, students in a course at Yale titled 3-D Modeling for Creative Practice developed a small library of program modules (also in Unity) for common actions that an XR developer might want to use.

These projects were course assignments, but because they were pushing at the edges of their respective fields, students' final products could not be assessed according to any traditional rubric. What constituted a successful project in these courses was their spirit of experimentation: a data visualization may be crudely realized, or a Unity script might be buggy. The important criteria in assessing these assignments was their exploration of creative ideas. One of the learning objectives of the VR Storytelling course is that the student will "identify stories that can be 'told' better through an experience." But what kinds of stories are those? This is a question to which we do not yet know the answer. These students are literally discovering the boundaries of XR capabilities while experimenting with technology on the cutting edge of their field, a valuable and all-too-rare educational experience. Sometimes experimentation is the point.

Integrating XR into Curricula

A 2019 report[18] from the US Department of Education's What Works Clearinghouse recommends the use of simulations, and XR specifically, to help students engage in complex problem-solving and interact more deeply with learning materials. For XR to be implemented in a pedagogically meaningful way, this report suggests that it is necessary for both the course and the curriculum as a whole to provide students with sufficient time to engage with complex problems.

Few academic programs have integrated simulations into their curriculum as thoroughly as nursing and other medical disciplines have. Indeed, it may be difficult for many programs to make available this kind of time for students to engage with XR technology across the curriculum. It can be done, of course, but as readers of EDUCAUSE reports know perhaps better than anyone, changing curricula in higher education is a lengthy process. In the meantime, there are other ways to create time for students to engage with XR technology.

Time and Skills

Hackathons in particular have been used to great effect at several participating institutions.[19] MIT has hosted an XR hackathon, Yale has hosted two, and Hamilton College sponsored a group of students to travel to one at another institution. These events were organized by a combination of campus units, some administrative (such as IT units) and some academic, with the participation and sponsorship of several external organizations. The specific academic programs involved in these hackathons naturally vary across institutions, as do the topics of the hackathons: Yale's hackathons were on global climate change, while the Hamilton students participated in tracks on topics such as smart homes and smart cities. More importantly, though, these hackathons provide students with the time and resources to engage in complex problem-solving and to engage deeply with a topic through the use of XR technology.

Time is just one issue in implementing XR in a way that is pedagogically meaningful; another is the technical ability of students. While XR is useful for providing skills-based education, ironically its use requires some skills in the first place. Anyone participating in a hackathon probably has some programming skills going in. But the same should not be assumed for students more broadly.

Even at an institution where technology literacy is integrated into the general education curriculum, it may be too steep a learning curve to ask students to learn to develop an XR application within the span of a single academic term.

Barnard College is one such institution where technology literacy is integrated into the general education curriculum, which is called Foundations and is organized around Modes of Thinking. One of these modes is Thinking Technologically and Digitally, which includes such things as computational thinking, programming, and digital arts and humanities. As is the case at many institutions, courses at Barnard can fulfill one or more requirements of the general education curriculum. A course that addresses Thinking Technologically and Digitally often contains a lab section in which students have access to relevant hardware and software. Instructors at Barnard may request support from the Instructional Media and Technology Services (IMATS) unit on various technologies. This support can take many forms, such as scheduling an IMATS staff member to come to class and provide instruction to students. IMATS also offers workshops to students and faculty on various technologies throughout the academic year, which is a common service model offered by many campus IT units and centers for teaching and learning.

Another method for integrating XR into the general education curriculum is by including it in a first-year experience course.[20] Florida International University (FIU) has offered such a course for several years, and in fact there are several different first-year experience courses on offer. Currently a new first-year experience course is being developed in which students will work with XR technology to explore issues such as design thinking and ethics in online spaces. A challenge that FIU faces in developing this course is that *it will require instructors to teach it*. Obvious, yes, but a course in which students use XR needs an instructor who knows how to use XR and is able to support the students. Instructors involved in this course will be supported by both the campus IT unit and FIU's Center for the Advancement of Teaching. Students and instructors will also be supported by the Miami Beach Urban Studios, a building-sized (16,000 square feet) makerspace-like facility that serves the campus community. Integrating XR into a first-year experience course and providing this level of support will allow students the time and resources needed to engage deeply with the technology.

Few institutions have been using XR technology in the classroom long enough to collect experimental data on its learning effects, but Yale is one of those institutions. As of this writing, the Yale School of Medicine has been participating in Yale University's Blended Reality Applied Research Project for approximately two years, and a team from the Department of Neuroscience has developed an AR app to visualize the brain (figure 4). This app will be integrated into some, but not all, lab sections of a neuroscience course in the fall 2019 semester. At the end of the semester, students' performance on course assessments will be compared: those who used the app versus those who did not. More clinical studies of this sort are needed to further explore the learning effects of XR technology in specific fields, for specific use cases, and for specific types of students.

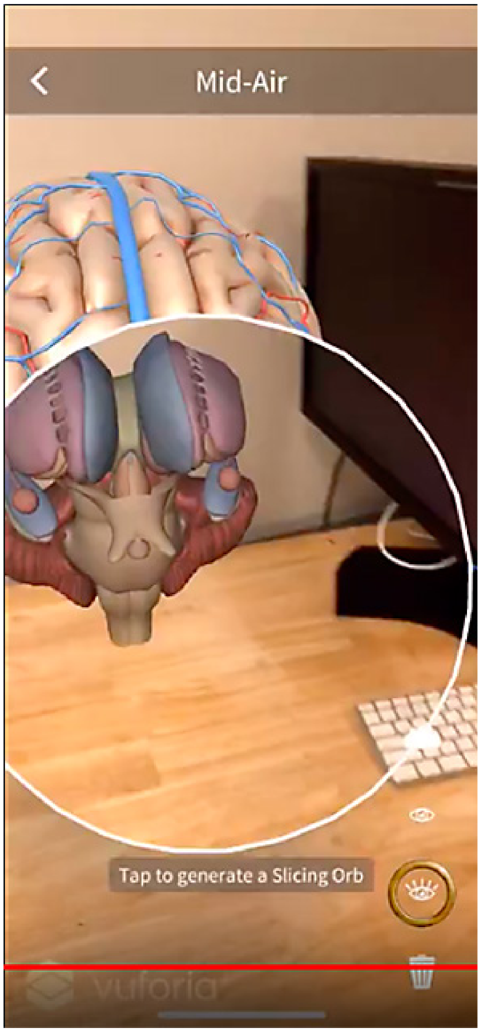

Figure 4. Sample image from a brain AR medical app from the Yale School of Medicine

Image courtesy of Michael Schwartz, Yale School of Medicine

Student Assessment

A recent article in *The Chronicle of Higher Education* lamented our lack of knowledge about the pedagogical impact of XR.[21] This concern was echoed by several interviewees for this project—even some from nursing programs, which have long recognized the value of simulations in teaching and learning. Indeed, the Institute of Medicine's 2000 *To Err Is Human* report[22] recommended that professional education across healthcare fields use simulations whenever possible when creating learning environments. A large body of research has since emerged about the pedagogical impact of simulations using manikins and standardized patient–actors in medical education. Research on XR simulations, however, is only beginning to emerge in medical education.

Research on XR in other fields lags even further behind. There is a growing body of research about the use of VR and AR for teaching a variety of subjects.[23] Much of that literature is highly focused, however, investigating the use of a specific technology for teaching a specific topic or in a specific course. Only a fraction of that literature compares the effectiveness of an XR technology with a non-XR option.

The present study was broader in scope than most of this previous research and focused on a range of XR technologies across institutions, though at each institution the focus was on only one or at most a handful of specific fields or courses. Because of the breadth of this study, we can at least start to answer the question about the pedagogical impact of XR.

The previous section discussed the integration of this technology into courses and across curricula. That is of course necessary, but once that integration is under way, the next step in any discussion of the effectiveness of XR (or any) technology for learning is its pedagogical impact on the student. This section briefly discusses methods that instructors at participating institutions used to assess student learning in courses and for assignments in which XR was used. Some of the points made earlier are repeated here, but they are drawn together into a discussion of XR-specific assessment methods.

Simulations are already widespread in nursing education, using manikins and standardized patient–actors. Instructors evaluate students' performances in these simulations according to predefined rubrics based on specific learning objectives and criteria. These criteria may also be built into an XR simulation, so that a student's performance is assessed throughout their interaction with the simulation. XR applications that are game-like, such as Cellverse, may use similar mechanisms. Although there is no standard rubric for assessing learning about the central dogma in biology, for example (or indeed in many STEM disciplines), there are inventories and assessment tools for the central dogma and other topics.[24] These tools can be built into biology simulations and used for assessment, so that students' performance is assessed throughout their interaction with the simulation, similar to how VR games are developed with built-in analytics. But instead of capturing key performance indicators (KPIs) about a user's actions within a game, an educational simulation may capture KPIs about a user's actions and behaviors that address the learning objectives. This is in fact how at least some existing XR simulations, such as Shadow Health, work: they are essentially computer-based training modules with an evaluation tool that grades the user's performance at the end of the simulation.

XR applications that simulate the physical world but are not designed as games, such as the Electrostatic Playground, might likewise capture KPIs about a user's actions. The Electrostatic Playground is designed as a space for exploration, however; unlike repairing an organelle in Cellverse or giving a patient an injection, there is no "correct" way to interact with subatomic particles in the Electrostatic Playground. In this type of simulation, a student's performance may be assessed through interactive exercises, like a hands-on quiz. These assessments may be built into the simulation, like end-of-chapter questions in a textbook. Just as important, such simulations should provide functionality to enable instructors to create their own assessments.

It can be challenging to assess student learning when experimentation is the point. This experimentation may be with the technology, as at Yale, where a group of students worked on developing a new controller and another group developed a library of Unity program modules. Or this experimentation may be with the subject matter, as at Syracuse, where students developed new interactive data visualizations. In either case, rubrics for evaluating student learning may not exist, given that these projects are pushing the boundaries of their respective fields. Even here, however, some useful guidelines emerge for how instructors can think about student assessment. Another student project that pushed the boundaries of the field was an assignment for a dance course at Barnard, where students produced a work of site-specific choreography: here the assessment rubric naturally focused on the choreography rather than the technology. But a central question in evaluating the choreography was whether the student factored the technology into the choreography. The dance piece was intended to be viewed on a small screen, which may affect the choreographic choices the student makes. In other words, a student assessment rubric might ask whether XR technology is being used thoughtfully in the context of the task.

Another example is the AR application visualizing the brain, developed by the Yale Department of Neuroscience. This was not a course assignment, but the programmer for the project was a student. No software requirements specification was created going into this project. Rather, over the course of developing this app, the project PIs and the developer met frequently to brainstorm and identify what was possible for the app, based on what they were learning about the technology as work progressed. In this way, the development process was flexible enough to accommodate new functionality as new software versions of the development platform were rolled out, and the application that was ultimately developed was informed by what the team learned throughout the process. In other words, a student assessment rubric might ask whether XR technology is being used flexibly enough to accommodate both changes in the technology itself and in the student's knowledge about the technology.

Factors That Influence Learning

The research question motivating this study is: **What factors influence the effectiveness of XR technologies for achieving various learning goals?** Before an XR technology can be used to achieve anything, however, it has to be adopted for use.

"What can we do in XR that we can't do otherwise?"

—Meredith Thompson, MIT

Factors That Influence the Adoption of XR

Two factors emerged as critical for the adoption of XR in pedagogy. The first is that the XR application must fit into instructors' existing practices. This is of course no different from the adoption of any other new technology: we all use new tools for old uses at first, until we figure out what the new tool is capable of. This is a central finding of research on diffusion of innovations: To be adopted, an innovation must be compatible with whatever existing systems are in place.[25] And to be adopted not just by one instructor but more widely, across a curriculum or a field, an XR application must fit into existing instructional methods. Many disciplines (such as nursing) have existing standards, or at a minimum existing curricula and instructional methods (as in biology), and XR must fit into such existing standards and practices. Over time, those standards and practices will change, influenced at least in part by XR. But at least at the beginning, an innovation must fit into existing ways of doing things.

The second factor influencing the adoption of XR is cost. Again, this is basic diffusion of innovations stuff: the cost of adopting an innovation cannot be too high. Cost may take the form not only of money but also of the time required to scale the learning curve, the cognitive load of using it, etc. For XR, all of these costs figure into instructors' calculations. Commercial XR applications, such as anatomy simulations published by traditional textbook publishers, may be quite expensive, and if a commercial simulation does not match the instructional goal, then an instructor or a program is unlikely to spend the money. (This was part of the motivation behind the Yale Department of Neuroscience developing its own AR application.) Even if an XR application does match the instructional goal, it must still be cost-effective—as easy to deploy, learn, and use as non-XR alternatives, for a similar or preferably lower cost. (This was part of the motivation behind the Morgan State project developing XR simulations for nursing education rather than using established simulations with standardized patient–actors.)

Factors That Influence the Effectiveness of XR

Only after an XR technology has been adopted for use in a course is it meaningful to ask what factors influence its effectiveness for achieving the learning goals of that course. Several factors seem to influence the effectiveness of XR, though further empirical research is needed on all of these.

The Fidelity and Realism of the Simulation

The more authentic an experience a simulation provides, the more valuable it is as a teaching tool. This is especially true in skills-based learning, such as nursing, where XR simulations are in competition, so to speak, with existing high-fidelity simulations such as those with standardized patient–actors. But this is also true for simulations in fields that are traditionally taught as more conceptual knowledge, the difference being that the contents of these simulations are outside the realm of human experience, so fidelity and realism must be defined differently. Humans have experience of electromagnetism, for example, but that experience is somewhat indirect: we have all played with magnets, but we can't see or feel magnetic fields directly. A simulation of electromagnetism (figure 5) must match current scientific understanding and must be updated regularly to keep it accurate as disciplinary knowledge changes. Equally important, an XR application designed as a teaching tool must be authentic; however, that authenticity is defined not by how well the simulation mirrors the physical world but rather by how well it supports "embodiment." To a certain extent, the XR user must engage in willing suspension of disbelief when entering a simulation, just as with any media content. The difference is that, for an educational simulation, the "fictional" world of the simulation must not only be internally consistent, as it should be with any story, but also be consistent with the physical world with which the user is familiar.[26] To be useful as a teaching tool, a simulation must be both accurate and convincing.

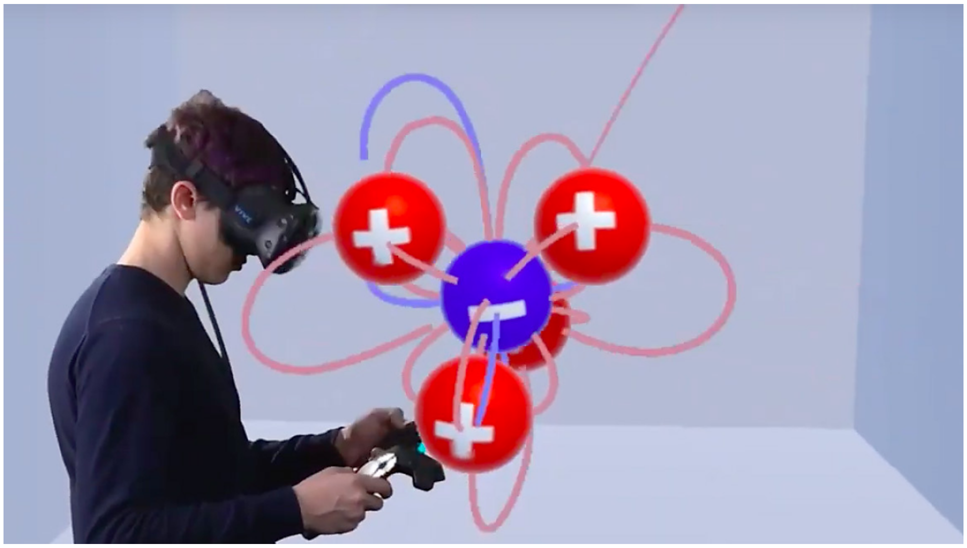

Figure 5. A student learning about electromagnetism using Electrostatic Playground
Image courtesy of John Belcher, MIT Department of Physics

The Ease of Use of the Hardware and Software

New technologies are often complicated or difficult to use. Over time and through multiple versions, interfaces change as developers learn more about use cases and usability. This has certainly been the case for XR technologies. We are already seeing some standardization on common and easy-to-use interfaces, such as arranging blocks of text in VR simulations in scrollable columns rather than in long lines (to avoid blurring at the edges of the user's field of view) and designing mobile AR applications to be operated one-handed (because the other hand is holding the smartphone). Interface development is even more critical for accessibility, such as captioning for users who are deaf or hard of hearing, and for controllers that are usable for those with mobility impairments. Generally standardized interfaces make a technology easier to use, as the interface is likely to be familiar even to a newcomer. (The iOS and Android smartphone operating systems have obvious differences, for example, but both rely on the desktop and icon metaphors that became familiar with the Apple Macintosh in the mid-1980s.) The ease of use of XR technology strongly influences its effectiveness for learning. A critical issue for the XR simulations being developed at Morgan State, for example, is that it is difficult, maybe impossible, to simulate fine motor actions, such as giving an injection, using a handheld controller. Morgan State—and probably any XR-based medical training—requires hand tracking, for example a VR glove or a Leap Motion controller.

Providing Something Not Available Any Other Way

An XR technology must enable the student to learn in a way that is not possible using any other media; otherwise, there is little incentive for either the student or the instructor to adopt the XR alternative and little reason to believe that it will be more effective than traditional instructional tools. XR does, however, enable learning in new ways: learning about cellular biology by exploring a cell as if it were a physical space, for example, or learning medical techniques by practicing them more times than would be possible in the physical world, or learning about architecture by developing data visualizations of real-time interactions between people and spaces. The physical world has inherent limitations: for example, a human being cannot shrink to fit inside a cell. XR technologies make it possible to overcome these limitations, thereby creating new learning opportunities.

An Increase in Students' Time-on-Task

Several interviewees for this project noted that XR technology motivated students to engage with course material for longer. It is not possible for this study to quantify the amount of this increase, as we didn't have access to the students at participating institutions during the course of this project to collect data on their time spent on coursework. However, this finding is consistent with other research on blended learning. Other researchers have found that increased time-on-task leads to increased performance on learning outcomes and that the use of blended learning techniques leads to increased time-on-task, due to the use of additional learning materials and additional opportunities for collaboration around those materials.[27] These findings seem to hold for XR technologies as well, suggesting that XR is a valuable contribution to blended learning.

A Spirit of Experimentation

The student, the instructor, and those providing support to the student and the instructor all must possess a spirit of experimentation. Even though XR technologies are starting to see some standardization, both hardware and software are still in a period of rapid development. Several interviewees for this project stated that some of the best student work with XR was the most unexpected. This applied to students, both individually and in groups, who went above and beyond the course assignment, or who were working on a specific project but were given free rein in how to accomplish it, or who simply developed their own idea for a project and realized it outside of any course. These students learned a great deal about both the technology and the subject matter; but just as important, they learned how to learn. They engaged in complex problem-solving and interacted deeply with their subject matter. For students to be able to engage in this kind of self-directed learning, they need freedom and flexibility, which requires buy-in from both the instructor and the institution. Instructors must be willing to let their students experiment in the context of a course or an assignment. Even more basic, though, is that XR technology must be freely available for students to use—for example, in a lab or a makerspace. The security of the hardware is a concern, but the lighter the touch, the better. One of the most important factors influencing the effectiveness of XR for learning is simply access to the technology. From there, instructors and institutions should follow where students lead.

Conclusion

XR technology is becoming more common, and its cost is decreasing. In this way, XR technology is likely to follow the familiar trajectory of so many other technologies on campus. Once upon a time, mobile devices were the subject of special projects to evaluate their use cases on campus;[28] now nearly all students have access to smartphones.[29] Some students are no doubt already arriving on campus with VR headsets, but this is still relatively rare: only about 4% of students have access to XR technology, according to the 2018 ECAR study of undergraduate students and information technology. As of this writing, however, a Google Cardboard–compatible headset costs only about $15, and the Google Cardboard smartphone app is free. XR technology will only continue to be more widely used on campus.

Once upon a time, learning management systems were, like mobile devices, the subject of special projects by campus IT units,[30] but now an LMS is deployed at nearly all US institutions.[31] Learning to develop XR applications—on any platform—has a fairly high learning curve. But at one time, so did developing a course site in an LMS. As XR technology matures, development platforms will become easier to use, leading to more development of XR materials for teaching and learning. Curricula are standardized in many fields, and even where this is not the case, instructors often share their teaching materials with colleagues. As more XR materials for teaching and learning are developed and disseminated, XR will increasingly become a standard piece of classroom technology, used by instructors, expected by students, and embedded in curricula (see figure 6).

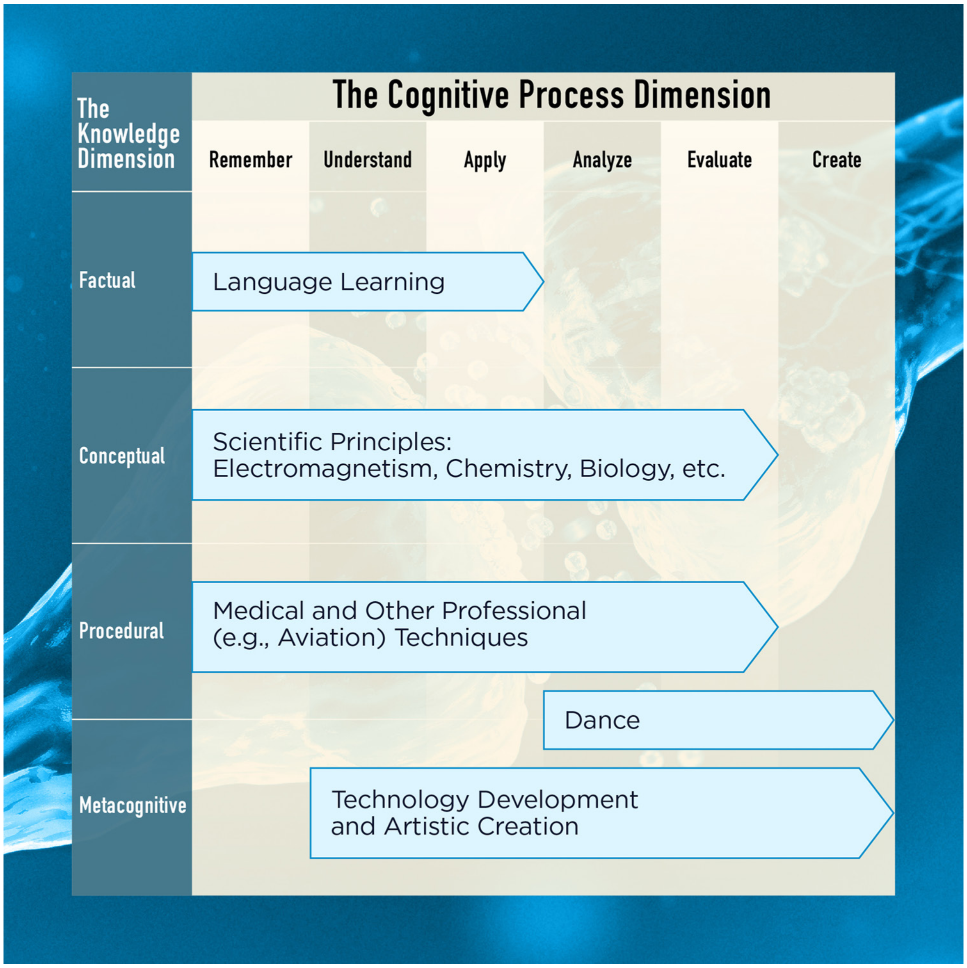

Figure 6. Examples of instructional activities using XR, mapped to revision to Bloom's Taxonomy of Educational Objectives[32]

Recommendations

Every institution of higher education is unique in its organizational structure and the resources it dedicates to IT and support for teaching and learning. The fields in which teaching and learning actually occur, however, have their own curricula, practices, and cross-institutional boundaries. XR, like any new technology in higher education, must be adopted both within fields and within institutions. This report takes a higher-altitude view of how XR technology is being integrated into institutions of higher education, not just in one course or at one institution but systematically. At the same time, part of the purpose of this report is to inform institutions of higher education that have not yet deployed XR technology about how they might start to do so most productively. This report therefore relies heavily on examples of XR in teaching and learning at institutions that participated in this study. These are summarized in table 1, along with the key findings of this study that they illustrate. Some of the examples and lessons learned that have been discussed in this report will therefore not be applicable to all institutions. Nevertheless, all recommendations are presented here for institutions of higher education that are interested in deploying 3D technologies, with the understanding that your mileage may vary.

"3D is our natural mode of being; it should be our natural mode of learning."

—Dan Pacheco, Syracuse University

Table 1. Key findings and associated case study evidence

<table>
<tr><th colspan="2">Key Finding</th><th>Case Studies</th></tr>
<tr><td colspan="2">XR technologies are being used to achieve learning goals across domains.</td><td>Learning factual knowledge such as vocabulary: language learning
Conceptual knowledge such as categorization and systems thinking: Cellverse, Electrostatic Playground
Procedural: techniques and methods, as in nursing education
Metacognitive: process and reflection on process, as in the choreography use cases at Barnard and Yale</td></tr>
<tr><td rowspan="3">Effective pedagogical uses of XR technologies fall into one of three large categories:</td><td>(1) Supporting skills-based and competency-based teaching and learning</td><td>Nursing education (e.g., the nursing program at Morgan State University and the Simulation Center at the Columbia University School of Nursing): students benefit from being able to repeat tasks to gain practice.</td></tr>
<tr><td>(2) Expanding the range of activities with which a learner can gain hands-on experience</td><td>Cellverse and Electrostatic Playground: providing a simulation of hands-on experience where that is otherwise not possible.</td></tr>
<tr><td>(3) Experimenting by providing new functionality and enabling new forms of interaction</td><td>Yale’s AR brain app, and choreography use cases at Barnard and Yale: experimental uses push the boundaries of interaction between a user and a digital representation of the phenomenon or object of study in a discipline.</td></tr>
<tr><td rowspan="2">Integrating XR into curricula faces two major challenges:</td><td>(1) Time</td><td>Hackathons and first-year seminars: ways to provide students with time to delve into XR technology</td></tr>
<tr><td>(2) Skills</td><td>First-year seminars and software development: ways to enable students to gain XR-specific skills</td></tr>
<tr><td rowspan="2">The adoption of XR in teaching requires two major factors:</td><td>(1) The technology must fit into instructors’ existing practices.</td><td>Simulations in nursing and Cellverse in biology: these XR uses fit into existing curricula and standards in these fields.</td></tr>
<tr><td>(2) The cost cannot be significantly higher than the existing alternatives that the instructor is already using.</td><td>Yale’s AR application and Morgan State’s XR simulations: these applications are being developed specifically as lower-cost alternatives to existing options.</td></tr>
<tr><td colspan="2">The effectiveness of XR technologies for achieving learning goals is influenced by several factors.</td><td>All case studies in this report illustrate this to some extent: why the researchers interviewed for this project decided to use XR in the first place, how XR was used by students, and all the established factors that impact the effectiveness of technology in the classroom.</td></tr>
</table>

For Instructors

- **Provide time for students to engage with XR and the subject matter.** For XR to be pedagogically meaningful in teaching and learning, students must have sufficient time to both scale the learning curve of the technology and engage with the learning material. It can be difficult to make this kind of time available, however, in the context of a course or across the curriculum. Hackathons hosted by institutions of higher education have been effective in providing students with the time and resources to engage deeply with a topic through the use of XR technology.
- **Integrate XR into courses that fulfill the institution's general education requirements.** For XR to be pedagogically meaningful in teaching and learning, students must have sufficient time to engage deeply with the technology and with the problem-solving enabled by it. Integrating XR into an institution's general education curriculum, perhaps as part of the larger theme of technology literacy and/or into a first-year experience course, is an effective method for introducing students to XR technology.
- **Provide support to students.** XR, like any new technology, has a learning curve. Students will need to scale that learning curve in order to use XR effectively, but there really is not a lot of time for this curve-scaling in a typical academic term. Instructors need to know how to use XR themselves in order to support students in their use of XR. Instructors should also bring in student support from other campus units, such as centers for teaching and learning.
- **Let students experiment.** XR is a new technology, and both developers and users are still discovering its affordances and boundaries. As with many new teaching tools, there is not yet a set of best practices for deploying XR for teaching and learning. Even as students are learning how to use XR, they may also be developing something new and pushing the bounds of their chosen field. Of course, it is challenging to assess student learning when the student—and often the instructor—is experimenting. The important question in this context is whether XR technology is being used thoughtfully in the context of the field.

For Institutions

- **Provide support to the campus community.** Students and instructors alike will need to learn to use XR technology. Students may be using it in the context of a course or an assignment and therefore have a short timeline for learning. Instructors may have a longer timeline, but they need more in-depth information as they integrate XR into their courses or assignments. Different service models will be appropriate for these different use cases, and some combination will probably be necessary, offered by collaborations between one or more campus units, such as IT units and centers for teaching and learning. Workshops on various specific XR tools, limited in scope and offered frequently, may be useful for both students and instructors. Classroom support may help instructors in their deployment of XR in their courses and provide students with more in-depth training than the instructor is able to provide. Train-the-trainer models may be effective for instructors: one instructor learns about and integrates a technology into a course and then helps colleagues to do the same.

- **Provide space for users to engage with XR technology.** For members of the campus community to be able to experiment with and learn to use XR technology, that technology must be freely available—for example, in a campus lab or a makerspace. Providing public access to XR has staffing implications, as the staff in the space must be able to support users with the technology. Likewise, the space must be staffed or monitored constantly to ensure the security of the hardware. That said, simple access is one of the most important factors influencing the effectiveness of XR for learning.
- **Encourage capacity-building.** Like many campus technologies, XR will be used across fields and by all types of institution-affiliated users. Supporting these diverse users and use cases will require staff from across campus units. Instructional designers will need to learn how to use and support the technology, while IT staff will need to learn how to support teaching and learning with it. Knowledge-sharing across campus units and traditional institutional silos will be critical. Creating cross-institutional working groups and building capacity within individual campus units will both be important for supporting XR technology on campus.
- **Participate in community-building.** Many institutions are adopting XR technology for teaching and learning, but often this process is entirely internal to the institution. There is a great need for support and information sharing across institutions concerning uses and practices for XR in teaching and learning and to enable the sharing of XR tools and content. The EDUCAUSE XR (Extended Reality) Community Group promotes discussion and support regarding these and other issues. Institutions should encourage instructors and staff involved with XR technology on campus to participate in this and other formal and informal interest groups.

For Future Research

- **More research is needed on the pedagogical impact of XR.** A body of research exists about the use of VR and AR for teaching and learning, but much of that literature focuses on the use of a specific technology for teaching a specific topic or in a specific course. This study was broader in scope than much previous research, spanning multiple technologies, topics, and institutions. But while this study provides a wide-angle view of the current state of the art and starts to map out a research agenda, that research agenda must be taken up by the XR community as a whole.
- **Intervention studies are needed.** Two types of intervention studies are particularly relevant for studying the effectiveness of XR technology for learning, and these study designs are not mutually exclusive. Pre–post studies will enable researchers to identify the impacts of XR technology on students. Trial studies will enable researchers to compare the effectiveness of an XR technology with that of a non-XR option. This is especially the case in fields where XR tools are competing, so to speak, with existing teaching methods—for example, simulations using XR versus those using manikins or standardized patient–actors in nursing education.

For Technology Development

- **Develop easier-to-use development platforms.** Several repositories of XR objects and experiences exist, as do several XR development platforms. It is relatively easy to download an educational XR application and use it as is. Likewise, it is relatively easy for a developer with knowledge of a development platform to develop a new XR application. What is not yet easy is for someone who is not a developer to develop a new XR application. There is great demand among instructors for exactly this functionality—the ability to develop custom XR applications for specific fields, courses, and use cases. For XR to be widely adopted in higher education, it will need to become easier to customize and serve in developing course-specific materials.
- **Contribute XR applications to repositories of learning objects.** Several repositories of open educational resources (OER) exist, such as MERLOT and Waymaker. These repositories provide a platform for instructors to share materials that they have created and to find materials shared by others. While there is demand among instructors for custom XR applications, some of this demand arises from a lack of sharing: given a choice, some instructors would probably rather not develop XR applications themselves. If more XR applications were shared via such repositories, they would no doubt be used as much as other forms of OER.[33]

- **Work with game designers.** Realism and authenticity are critical in XR simulations, particularly in fields where education and training are skills-based. This is not a call to "gamify" skills-based education. Rather, this is a call to work with developers who have experience designing realistic simulated environments. The gaming industry has been developing ever-more realistic graphics for VR and AR games for years.
- **Build instructional scaffolding into applications.** Again, this is a call to work with game designers, as the gaming industry also has long experience at building key performance indicators into games, to track and promote player progression. Educational applications need to do the same, that is, track student progress and promote student success. Just as KPIs are different in different games, so too should they be different in different educational applications, based on standard rubrics and assessment tools in different fields.

Acknowledgments

The author wishes to thank all of the individuals who agreed to be interviewed for this project. Without your hard work and creativity in using XR, and your willingness to share your insights about it, this report would literally not have been possible.

Special thanks to Dr. Joylin Anderson-Calhoun, Nurse Educator at the Jesse Brown VA Medical Center in Chicago. Anderson-Calhoun was the PI for the nursing simulation research described in this report, but sadly she passed away in 2018 and did not get to see it completed. Thanks to the faculty and researchers in the nursing program at Morgan State University for continuing this important work. Thanks also to those researchers at Morgan State University for the Chesley "Sully" Sullenberger story.

Thanks to the members of the EDUCAUSE XR Community Group and the IEEE ICICLE XR for Learning and Performance Augmentation SIG, who would frequently post XR-related news to their respective listservs, which informed this study.

Thanks also to the EDUCAUSE team—D. Christopher Brooks, Director of Research; Malcolm Brown, Director of Learning Initiatives; and Jim Burnett, Director, Membership Development—for being constant and vital partners in the development of this project. Additional thanks to Susan Grajek, Vice President, Communities and Research, and Mark McCormack, Senior Director of Analytics & Research, for their careful reviews of this report in manuscript form; Kate Roesch, Data Visualization Specialist, and Scott Ladzinski, Visual Design Lead, for their artistic vision; Gregory Dobbin, Senior Editor, and the publications team for making my writing become much betterly than it really would otherwise probably being; and Lisa Gesner, Content Manager, Marketing, for keeping our eye on the ball throughout the process.

Finally, special thanks to HP for conceiving and supporting the Campus of the Future initiative, and Gus Schmedlen, Vice President, HP Worldwide Education, for his tireless efforts to connect the EDUCAUSE team with those using XR technology around the world.

Appendix A: A Note on Terminology

As with any rapidly changing technology and marketplace, the terminology around XR technologies is highly fluid. However, four terms crop up often and, to a certain extent, overlap: virtual reality (VR), augmented reality (AR), mixed reality (MR), and extended reality (XR). Many discussions of these technologies reference the concept, first proposed in the mid-1990s, of a "virtuality continuum" (see figure A1), from entirely real to entirely virtual.[34] On one end of this continuum is the physical world, and on the other end is VR— an entirely simulated environment. In between those two poles is MR, which encompasses AR and augmented virtuality (AV)—AR is the physical world augmented with virtual objects, while AV is a simulated environment augmented with physical objects. Even the authors of early papers about the virtuality continuum admit that as graphics rendering technology improves, it will become increasingly difficult to determine whether augmentations, and even the environment being augmented, are physical or virtual. We are not yet at that point in technology development, but we are perhaps not far off: think about how realistic computer-generated imagery (CGI) in movies can be. Nevertheless, in the virtuality continuum, both AR and AV are points on the spectrum of MR.

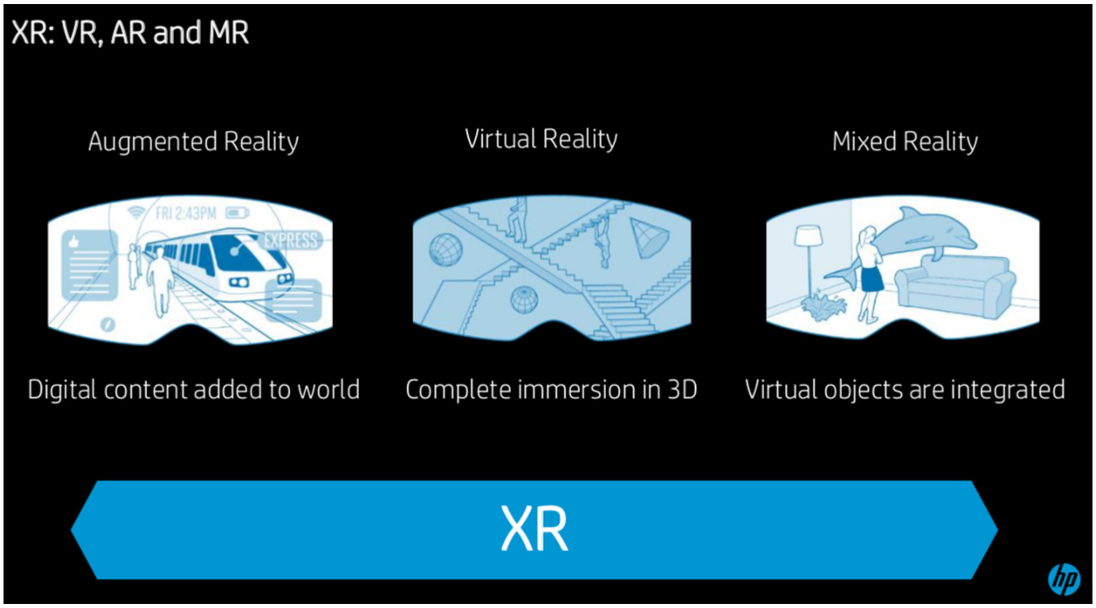

Figure A1. Significant points on the virtuality continuum

Since those early publications on the virtuality continuum, these terms have shifted. The term AV is no longer widely used. The term AR is used to mean the physical world augmented with virtual objects, but those virtual objects are static, mere overlays atop the physical world. Many AR applications have been developed for museums and for specific museum exhibits. The Franklin Institute in Philadelphia, for example, deployed an excellent AR app for the touring Terracotta Warriors exhibit. The term MR (and the emerging term "hybrid reality") is also used to mean the physical world augmented with virtual objects, but those virtual objects are interactive: the user can affect the state and behavior of these virtual objects, and these virtual objects may also affect the state and behavior of physical objects. A research project at Harvard University, for example, is developing MR overlays for learning electronics in which the user can see and change the flow of electricity and the magnetic fields around a simple audio speaker.

The use of these terms in association with commercial products is where things often get confusing. The HTC VIVE, for example, is marketed as a VR headset, but some newer models contain forward-facing cameras (also called "pass-through" cameras) that allow the user to view the physical world in the headset. Some newer models of Microsoft Windows–compatible headsets also contain pass-through cameras and are marketed as mixed reality headsets.

A cardinal rule of educational technology is that the technology used should follow from the educational use. VR, AR, MR, and even AV all have potential pedagogical uses. Part of the purpose of this report is to explore and suggest what those purposes may be. To include the broadest possible range of simulation-based technologies in discussions about their instructional use, therefore, EDUCAUSE has opted to use a broader term: extended reality (XR).[35]

Appendix B: Methodology

This study used the multiple case study method,[36] with the phenomenon under study being the use of XR technology for teaching and learning. Participating institutions were selected as exemplary cases:[37] institutions that participated in phase 1 of the Campus of the Future project were selected because of their depth of experience with XR technology and the larger number of use cases on campus; institutions with little or no prior experience with XR were selected specifically to be as different from these phase 1 institutions as possible.

A total of 17 educational institutions in the United States participated in this research project (see appendix C). A total of 33 interviews were conducted with 36 individuals at these institutions between January and May 2019. The interviewees spanned a wide range of jobs: instructors at all levels, deans and directors of academic units, librarians, instructional designers and directors of campus centers for teaching and learning, and C-level institutional leadership. These individuals were identified via snowball sampling, starting with the individual who is HP's primary institutional contact for the Campus of the Future project.

The primary data collection method for this project was semi-structured interviews. These interviews elicited detailed information about the interviewees' involvement in using XR technology. The interviews were supplemented by document analysis: where they were available and interviewees were willing to share them, course syllabi and research proposals were collected for courses and projects in which XR technology was used. Further, project teams at some participating institutions had created blogs to document the progress of XR-related projects; these posts became a data source about use cases on campus. Similarly, news articles in campus publications and the higher education press about participating institutions provided some information about campus use cases. Finally, some interviewees had published articles, or referred to publications by their colleagues, about XR in their discipline. These documents were used primarily to inform the creation of interview prompts.

Appendix C: Participating Institutions

A total of 17 educational institutions in the United States participated in this research project:

- Barnard College
- Bryant University
- Bucks County Community College
- Columbia University
- Dartmouth College
- Florida International University
- Foothill-De Anza Community College District
- Hamilton College
- Harvard University
- MIT
- Morgan State University
- The New School
- North Carolina School of Science and Math
- Syracuse University
- University of Pennsylvania
- Wake Technical Community College
- Yale University

These institutions were not representative—nor were they intended to be—of the state of higher education in the United States or globally. These institutions were selected as critical cases;[38] that is, they were chosen specifically for their informativeness about the use of XR in higher education. Institutions with prior XR experience are naturally going to be further down the road of implementation and deployment—and integration of the technology into teaching—than institutions with little or no prior XR experience. The wider the range of XR experience at participating institutions, the more informative these cases could be.

Some of the institutions that participated in this study also participated in the previous Campus of the Future project, described in the 2018 *Learning in Three Dimensions* report. Those institutions are mostly four-year, doctoral, research-focused institutions, and they had at least a year's worth of experience with XR when this project began. Institutions with little or no prior XR experience were therefore selected specifically to be as different from these as possible. These less experienced institutions were those with smaller student populations (e.g., Barnard College and Morgan State University) or that serve a different student population (e.g., community colleges).

The makeup of these participating institutions was as follows:[39]

- Most were four-year doctoral universities with high or very high research activity.
- One was a four-year master's institution: Bryant University.
- Three were four-year baccalaureate institutions: Barnard College, Hamilton College, and Foothill College (one of the two campuses of the Foothill-De Anza Community College District).
- Three institutions were community colleges: Bucks County and Wake Tech Community Colleges are two-year associate's colleges. Foothill-De Anza Community College is actually a community college district of two campuses, one a two-year associate's college and one a four-year baccalaureate college.
- One institution was a historically black college or university (HBCU): Morgan State University.
- One institution was a high school: the North Carolina School of Science and Math (NCSSM), a two-year public residential high school with a focus on STEM disciplines.

The *Learning in Three Dimensions* report presented a broad brushstroke overview of XR technology in higher education. Because this study delves deeper into the adoption and implementation of XR technology, it consequently casts a wider net of institution types.[40]

Notes

1. Gus Schmedlen, "Building the Campus of the Future," *The Garage*, November 1, 2017.

2. Jeffrey Pomerantz, *Learning in Three Dimensions: Report on the EDUCAUSE/HP Campus of the Future Project*, research report (Louisville, CO: ECAR, August 2018). The *Learning in Three Dimensions* report focused on 3D technology rather than XR technology, which is the focus of this report. This is because the phase 1 study, described in the earlier report, included investigation of the use of 3D scanning and 3D printing technology. While HP continued to provide 3D scanners and 3D printers to participating institutions during phase 2 of the project, this study focused more narrowly on VR and AR technology.

3. See, for example, Zahira Merchant, Ernest T. Goetz, Lauren Cifuentes, Wendy Keeney-Kennicutt, and Trina J. Davis, "Effectiveness of Virtual Reality-Based Instruction on Students' Learning Outcomes in K-12 and Higher Education: A Meta-Analysis," *Computers & Education* 70 (January 2014): 29–40; Iulian Radu, "Augmented Reality in Education: A Meta-Review and Cross-Media Analysis," *Personal and Ubiquitous Computing* 18, no. 6 (August 2014): 1,533–43.

4. Richard E. Clark, "Media Will Never Influence Learning," *Educational Technology Research and Development* 42, no. 2 (June 1, 1994): 21–29.

5. Barbara Means, Yukie Toyama, Robert Murphy, Marianne Bakie, and Karla Jones, *Evaluation of Evidence-Based Practices in Online Learning: A Meta-Analysis and Review of Online-Learning Studies* (Washington, DC: US Department of Education, January 2009).

6. Diana G. Oblinger, *Game Changers: Education and Information Technologies* (Boulder, CO: EDUCAUSE, 2012).

7. The first flight simulator, for training pilots to fly biplanes, was created in 1910. The first computerized flight simulator—the precursor to all modern flight simulators—was developed in the early 1950s. For a brief history of flight simulators, see Karolina Prokopovič, "What Do You Know About the Evolution of Full Flight Simulators?" *Aviation Voice*, June 7, 2017.

8. Institute of Medicine, *To Err Is Human: Building a Safer Health System* (Washington, DC: The National Academies Press, 2000).

9. Daryl Jones, Imogen Mitchell, Ken Hillman, and David Story, "Defining Clinical Deterioration," *Resuscitation* 84, no. 8 (August 2013): 1,029–34.

10. Jennifer Legault, Jiayan Zhao, Ying-An Chi, Weitao Chen, Alexander Klippel, and Ping Li, "Immersive Virtual Reality as an Effective Tool for Second Language Vocabulary Learning," *Languages* 4, no. 1 (March 2019): 13.

11. By enabling the learning of abstract concepts to at least partly become the gaining of a skill, the use of XR as an educational technology is consistent with the idea from cognitive science of "embodied cognition." This idea is complex, and there are multiple strands of research around embodied cognition, but to dramatically oversimplify: Embodied cognition suggests that "cognition" involves not only the brain but also the body and its movements through the environment. In other words, learning and understanding can be said to be the development of behaviors appropriate to a situation. By expanding the range of activities with which a learner can gain direct, hands-on experience by making "physical" the nonphysical, XR technology increases the scope of the environment that can be integrated into embodied cognition. See, for example: Andrew D. Wilson and Sabrina Golonka, "Embodied Cognition Is Not What You Think It Is," *Frontiers in Psychology* 4 (2013): 1–13.

12. Meredith M. Thompson, Annie Wang, Dan Roy, and Eric Klopfer, "Authenticity, Interactivity, and Collaboration in VR Learning Games," *Frontiers in Robotics and AI* 5 (December 19, 2018).

13. Sue Workman, "Mixed Reality: A Revolutionary Breakthrough in Teaching and Learning," *EDUCAUSE Review*, July 30, 2018.

14. James J. Gibson, *The Ecological Approach to Visual Perception* (Boston: Houghton Mifflin Harcourt, 1979); Donald Norman, *The Design of Everyday Things* (New York: Basic Books, 1988).

15. Amber Bartosh and Bess Krietemeyer, "Virtual Environment for Design and Analysis (VEDA): Interactive and Immersive Energy Data Visualizations for Architectural Design," *Technology|Architecture + Design* 1, issue 1 (2017): 50–60; Bess Krietemeyer, Brandon C. Andow, and Anna H. Dyson, "Human-Facade-Interaction: Constructing Augmented Reality Simulations for Co-Optimizing Dynamic Building Skin Performance," *MRS Proceedings* 1800 (2015).

16. Luka Crnkovic-Friis and Louise Crnkovic-Friis, "Generative Choreography Using Deep Learning," ArXiv:1605.06921 [Cs], May 23, 2016.

17. Justin Berry, Lance Chantiles-Wertz, and Isaac Shelanski, " The Clamshell: Rethinking the Virtual Reality Interface," in 2019 IEEE Games, Entertainment, Media Conference (GEM), 1–5, 2019.

18. Nada Dabbagh et al., "Using Technology to Support Postsecondary Student Learning: A Practice Guide for College and University Administrators, Advisors, and Faculty," Washington, DC: Institute of Education Sciences, What Works Clearinghouse (WWC 20090001), Washington, DC: National Center for Education Evaluation and Regional Assistance (NCEE), Institute of Education Sciences, US Department of Education, 2019.

19. A hackathon is a "design sprint"-like event, often over a weekend or a few days, in which participants collaboratively develop one or more software programs or other technologies to address a specific project or creative problem. Hackathons have been used to great effect in open-source communities, such as the Wikimedia Hackathons, at which participants work on the technologies behind Wikipedia, and on large-scale social issues that may be best addressed collaboratively across sectors, such as the future of urban environments.

20. US Department of Education, Institute of Education Sciences, "First Year Experience Courses," What Works Clearinghouse, July 2016.

21. Beth McMurtrie, "Virtual Reality Comes to the Classroom," *Chronicle of Higher Education*, May 27, 2019.

22. Institute of Medicine, *To Err Is Human*.

23. Merchant, Goetz, Cifuentes, Keeney-Kennicutt, and Davis, "Effectiveness of Virtual Reality-Based Instruction; Radu, "Augmented Reality in Education; and Marc Ericson C. Santos, Angie Chen, Takafumi Taketomi, Goshiro Yamamoto, Jun Miyazaki, and Hirokazu Kato, "Augmented Reality Learning Experiences: Survey of Prototype Design and Evaluation," *IEEE Transactions on Learning Technologies* 7, no. 1 (January 2014): 38–56.

24. The central dogma of molecular biology is an explanation of the flow of genes, from DNA to RNA to proteins. Dina L. Newman, Christopher W. Snyder, J. Nick Fisk, and L. Kate Wright, "Development of the Central Dogma Concept Inventory (CDCI) Assessment Tool," *CBE—Life Sciences Education* 15, no. 2 (October 13, 2017).

25. Everett M. Rogers, *Diffusion of Innovations*, 5th ed. (New York: Free Press, 2003).

26. J.R.R. Tolkien, "On Fairy-Stories," in J.R.R. Tokien, *The Tolkien Reader*; and John McCoy and Tomer Ullman, "Judgments of Effort for Magical Violations of Intuitive Physics," *PLoS ONE* 14, no. 5 (May 23, 2019).

27. Means, Toyama, Murphy, Bakie, and Jones, *Evaluation of Evidence-Based Practices in Online Learning*.

28. Yvonne Belanger, "Duke University iPod First Year Experience Final Evaluation Report," Duke University, June 2005.

29. Joseph D. Galanek, Dana C. Gierdowski, and D. Christopher Brooks, "ECAR Study of Undergraduate Students and Information Technology, 2018," research report (Louisville, CO: ECAR, October 2018).

30. Caroline Corrigan, "ITS Votes to Transition from Blackboard to Sakai by 2014," *The Daily Tar Heel*, October 18, 2010; "Fall 2015 Yale Canvas Pilot: Final Report of the Working Group," February 3, 2015.

31. Jeffrey Pomerantz and D. Christopher Brooks, "ECAR Study of Faculty and Information Technology, 2017," research report (Louisville, CO: ECAR, October 2017).

32. Lorin W. Anderson and David R. Krathwohl, eds., *A Taxonomy for Learning, Teaching, and Assessing: A Revision of Bloom's Taxonomy of Educational Objectives, Complete Edition* (New York: Addison Wesley Longman Inc., 2001).

33. Redstone Strategy Group, "Understanding the Global OER Landscape," William and Flora Hewlett Foundation, April 8, 2019.

34. Paul Milgram and Fumio Kishino, "A Taxonomy of Mixed Reality Visual Displays," *IEICE Trans. Information Systems* E77-D, no. 12 (December 1, 1994): 1,321–29.

35. In particular, see the EDUCAUSE XR (Extended Reality) Community Group.

36. Robert E. Stake, *Multiple Case Study Analysis*, 1st ed. (New York: The Guilford Press, 2005).

37. Robert K. Yin, *Case Study Research and Applications: Design and Methods*, 6th ed. (Los Angeles: SAGE Publications, Inc., 2017).

38. Michael Quinn Patton, *Qualitative Research & Evaluation Methods: Integrating Theory and Practice*, 4th ed. (Thousand Oaks, CA: SAGE Publications, Inc., 2014).

39. This analysis was conducted using variables from the Carnegie Classification of Institutions of Higher Education, 2018 Update Public File.

40. A note about the population studied here: The institutions that participated in this study were not representative—nor were they intended to be—of the state of higher education in the United States or globally. Indeed, it would probably have been impossible to draw a representative sample of institutions for this study. To draw a representative sample from a population, you first have to know what is being represented. The Carnegie Classification of Institutions of Higher Education data files list all degree-granting institutions of higher education in the United States. The most recent Carnegie data file could be used to define the population. However, it would have been impossible to define a sampling frame, as (even after this study) we cannot identify every institution of higher education in the United States that has adopted XR technology.