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Emerging Learning Technologies for Education on Sustainability Topics

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ABSTRACT

CONTEXT
In this work, we explore the role that emerging learning technologies (e.g., mixed reality, artificial intelligence, internet of things) can play in engaging individuals to learn about sustainability topics.

PURPOSE OR GOAL
Our primary goal is to answer the question:
How do interactions with emerging technologies support the development of mental models on sustainability topics?
This question comprises two sub-questions along the lines of our conceptual framework grounded in constructionism and mental models for learning:
How and in what ways do physical interactions with emerging technologies engage learners in learning about sustainability topics?
How do the mental models developed as a result of such interactions impact learners' understanding of sustainability topics?

APPROACH OR METHODOLOGY/METHODS
We conducted a technology review, similar to a literature review, to understand the current state of the art in emerging learning technologies. Our review is informed by a conceptual framework comprising the learning theories of constructionism and mental models. Our current review is not limited to a particular age group. In the future, this work will inform technology and intervention design to support undergraduate engineering students in understanding sustainability issues such that they are cognizant of them in their engineering practice.

ACTUAL OR ANTICIPATED OUTCOMES
This work has resulted in a synthesis of emerging learning technologies to learn topics of sustainability. The conceptual framework guiding the synthesis brings to light how hands-on constructionist learning experiences using emerging technologies can help support the development of mental models on an urgent topic of concern. This study also informs future work with undergraduate engineering students who make decisions throughout their careers with implications for sustainability.

CONCLUSIONS/RECOMMENDATIONS/SUMMARY
This work is a preliminary exploration of current learning experiences that use emerging technologies for sustainability education and will inform our future technology and intervention development work.

KEYWORDS
Emerging technologies, sustainability, mixed reality, artificial intelligence

Introduction

Anthropogenic climate change presents an existential risk to myriad human and animal communities across the globe (Beard et al., 2021; Butler, 2018; Ord, 2020; Pontzer, 2021; Richards et al., 2021). Algorithms implemented in digital technologies have the capacity to drive attention, shape beliefs, and affect resource allocation (Barocas & Selbst, 2016; Bessi et al., 2016; DeVito, 2017; Mehrabi et al., 2021; Noble, 2018; O'Neil, 2016; Wachter-Boettcher, 2017). Automated technologies can lead to massive displacements in the workforce and exacerbate wealth inequalities (Acemoglu & Restrepo, 2018, 2019; Allen, 2017; Moll et al., 2021; Peng et al., 2018; Robinson, 1977; Wadley, 2021). In the example of climate change, engineers' activities can range from actions that exacerbate these ecological and social changes (Erftemeijer & Robin Lewis, 2006; Gibbs, 2012; Gorlenko & Timofeeva, 2019; McCartney, 2009; Sengupta, 2017) to actions that mitigate them (Fork & Koningstein, n.d.; Head, 2009; Lawlor & Morley, 2017; Meyer & Weigel, 2011; Sikdar, 2003). In these and similar scenarios, engineers are making decisions that can have far-reaching implications for SESs in myriad ways. Other examples of this work abound throughout the National Academy of Engineering's (NAE) Grand Challenges for Engineering or the United Nations' Sustainable Development Goals (Bleischwitz et al., 2018; Rahimifard & Trollman, 2018). They include impacts on the food-energy-water nexus, securing cyberspace, and developing technologies to address biological diseases.

Ideally, engineers will work to account for effects on SESs in their design considerations. Publications from the NAE emphasize the importance of engineers considering social and environmental impacts of engineering work in their decisions (Allenby, 2004; NAE, 2005). The Accreditation Board for Engineering and Technology (ABET) recognizes the importance of accounting for social, political, environmental, and economic factors in design solutions in two of their accreditation criteria (ABET, 2019). However, despite the importance of engineers considering the impacts of their work on such systems, there is research that suggests engineering students are not prepared to do this (Cech, 2014). On the contrary, Cech's work suggests engineers may dissociate social considerations from technical aspects of their work, a phenomenon termed socio-technical dualism (Faulkner, 2000).

In this paper, we explore how emerging learning technologies can help individuals make sense of topics that constitute broad system-level concepts and have been previously difficult to understand due to complexity and scale using prior traditional hands-on learning approaches. We define learning technologies as those designed or used to enhance the user's learning experiences (Scheffel et al., 2019) by simulating real life contexts, or generating educational models (Kinshuk, 2004). Emerging learning technologies provide opportunities to understand sustainability-related concepts in *virtually* hands-on ways that can create rich educational experiences. This review will inform our future work technology development work, and we are conducting this preliminary exploration because of the lack of similar work grounded in learning theories. The two learning theories of interest are that of constructionist learning (Papert, 1980; Paert & Harel, 1991) (an affordance of some emerging technologies) and mental models (Johnson-Laird, 1983; Morris and Rouse, 1986) (a promising approach to understand mindsets towards sustainability topics).

Approach

The research question guiding our work is:

> How do interactions with emerging technologies support the development of mental models on sustainability topics?

The review is informed by a conceptual framework comprising constructionism and mental models. The conceptual framework is motivated by the promise of constructionist learning principles in developing embodied understandings of topics, and mental models in informing how individuals think about complex sociotechnical issues. Keeping the two aspects of our conceptual framework in mind, we ask two sub-questions

> How and in what ways do physical interactions with emerging technologies engage learners in learning about sustainability topics?
>
> How do the mental models developed as a result of such interactions impact learners' understanding of sustainability topics?

Since this review is unique in the sense that much of the prior work in the space of emerging technologies has not been captured in academic literature, we take a non-traditional approach to our review process, by looking for relevant work in both academic and non-academic contexts. This review by no means is a systematic review. The primary aim of this work is to gather sources from a variety of sites to initiate a working understanding of how emerging learning technologies are being used for education on sustainability topics. We carried out searches in the Journal Storage (JSTOR) database, Google Scholar, Google News, and Google more generally using search terms like "vr and sustainability," "ar and sustainability," "iot and sustainability," "sustainability education and technology," and "emerging tech in education" until ten consecutive searches did not meet our search criteria. We concluded our searches on July 21, 2021. Our inclusion criteria for the technology/sources that we share in the next section, included:

- work at the convergence of emerging technologies, sustainability, and sustainability education
- work that reported on new technologies or empirical studies of new technologies (and not popular culture review articles)
- work that represented new and evolving studies, especially when searching Google News

Review

Below, we share the findings from our technology review organized to answer our two questions. Under the sub-heading of "user interaction," we provide the answer to the first research question - How and in what ways do physical interactions with emerging technologies engage learners in learning about sustainability topics? Under "intended outcomes," we answer the second question - How do the mental models developed as a result of such interactions impact learners' understanding of sustainability topics? We also categorize the sources into those that use augmented reality (AR), virtual reality (VR), and Internet of Things (IoT) technologies. Out of all the searches made on JSTOR, Google Scholar, Google News and Google (general), the examples below were chosen because they were the most recent and relevant out of those pertaining to the convergence of emerging technologies, sustainability and education.

Augmented Reality

Technology 1.1. Corona's AR experience to teach sustainability

User interaction: Corona launched an augmented reality experience for World Oceans Week that attempts to raise awareness about personal plastic consumption. It shows users a year's worth of their plastic consumption to demonstrate their footprint and provides tips on reducing individual footprints. Users are asked questions about their consumption habits in the app and given an estimation of their annual footprint. Footprints are visualized by colorful pieces of AR plastic that wash over the physical world before the user is transported to a "polluted paradise" meant to highlight the effects of pollution in nature. Finally, users are prompted to reduce their footprint. (Powis, 2021)

Intended outcomes: This interaction allows users to visualize a sustainability concept that was previously difficult to demonstrate effectively. Through visualizations, the user is encouraged to generate a more lasting and impactful mental model for their approaches surrounding sustainability. Additionally, the experience provides explicit suggestions for greater personal sustainability, which, when paired with the heavy emphasis on personal impact, will likely leave a more lasting effect on the user than traditional mediums of education. (Powis, 2021)

Technology 1.2. : An Eagle Scout in Lowell gifted his 4th-grade teacher his Eagle Scout project, an AR table that uses sand to create topographical models.

User interaction: Students manipulate sand in a wooden box by hand or with tools. A sensor and projector are used alongside software to generate and project elevation lines and colors to convey the depth of the sand. Students can create their own topography and use hand gestures to generate rain and observe runoff and other environmental phenomena (Bell, 2021).

Intended outcomes: This is a very hands-on application of AR and can help the students easily conceptualize and visualize the concepts they are learning. The students are being taught various environmental topics, including glacial activity, topography, drainage, the water cycle, and flood and drought conditions. AR enables a physical and touchable model to be easily reused and adaptive, making the learning process itself more sustainable as well. The students can generate lasting mental models by drawing connections between physical phenomena and their environmental effects, such as flooding and droughts, relevant sustainability topics.

Technology 1.3. AR Butterfly Gardens

User Interaction: With a smartphone or tablet, the user takes advantage of AR software to observe a virtual butterfly greenhouse with many different species of butterflies projected around their surroundings. The software allows the user to zoom in on specific butterflies with the virtual tracking telescope and allows them to tap on the butterfly to learn more about its respective species. It is also possible for the user to "breed" butterflies and observe their life cycle (Tarng et al., 2015).

Intended Outcomes: Researchers at the National Hsinchu University in Taiwan developed this project intending to increase the public's knowledge regarding insect ecology and the importance of butterflies in maintaining the environment. In recent years, Taiwan has seen an overall decrease in the butterfly population as well as a decrease in the range of species, making this project timely (Tarng et al., 2015).

Technology1.4. “Seeing the Invisible": an AR art Gallery

User interaction: This collaboration between 13 botanical gardens worldwide replaces the traditional gallery or museum setting of art demonstrations with an AR experience. Individuals can view 13 virtual art pieces in AR upon visiting one of the participating botanical gardens from September 2021 to August 2022. The Jerusalem Botanical Gardens organized the project in conjunction with the Outset Contemporary Art Fund. The art itself focuses on themes of nature, the environment, and sustainability and emphasizes the boundaries between art, technology, and nature. The app allows viewers to view AR art galleries when they enter any participating gardens. The experience attempts to replicate the real life experience of navigating a physical gallery, and users are to view the art in the space as if they were physical pieces (Maor & Haring, 2021)

Intended outcomes: The integration of technology into an artistic product helps to demonstrate the versatility and successful use of AR even outside of its traditional applications. The use of AR makes this art more accessible and sustainable than traditional exhibits, again demonstrating the potential of AR and other emerging technologies to increase access with less potential environmental strain. Finally, the art itself focuses on themes of sustainability and ecological conservation. Viewers begin to develop a more robust and inclusive mental model of sustainability that goes beyond the traditional areas of thought such as education or industry. (Maor & Haring, 2021)

Technology 1.5. AR for Understanding Wildlife and Conservation

User Interaction: With a smartphone or tablet, children watch their reading come to life with an AR support tool designed to enhance their learning of conservation and environmental sustainability. Students may hold their devices to a page to interact with the Panda featured in the book. They can rotate and move objects around and make the Panda bigger or smaller (Lee & Yoon, 2020).

Intended Outcomes: This technology was used to study the extent to which an AR enhancement to a children's book would improve children's understanding of conservation, wild animals, and environmental sustainability. The AR element is intended to encourage a "learner-centered" learning environment. With a broader spectrum of sensory information available to the learner, students can interact with information in a way that works best for them, allowing for full immersion in the subject matter. Combining emotive learning with facts and statistics, this technology aims to better engage children in conservation and wildlife topics, sparking empathy within the child and conversation and collaboration among the group of students using the tool (Lee & Yoon, 2020).

Technology 1.6. EcoMOBILE: Integrating augmented reality and probeware with an environmental education field trip

User Interaction: The EcoMOBILE project combines an AR experience with the use of environmental probe wear during a field trip to a local pond environment. The activities are designed to address different ecosystem science learning goals for middle school students and ultimately aid in understanding and interpreting water quality measurements. Students use the AR application, FreshAIR to navigate the pond environment and observe virtual media and information overlaid on the physical pond. Students can collect water quality measurements at designated AR hotspots. (Kamarainen et al., 2013)

Intended Outcomes: Combined use of technologies promoted student interaction with the pond and with classmates in a more student-centered format than traditional teacher-directed. The AR helped students gain deeper understandings of the principles of water quality measurement because of its ability to help students engage in activities that resemble scientific practice. (Kamarainen et al., 2013)

Technology 1.7.: Comparing VR and AR within the training pipeline of a construction company

User Interaction: This Slovakian study tests how the implementation of VR and AR in teaching construction can add efficiency. The current problem within the school system is the constant pressure to keep up with the forever evolving and rapidly changing world of technology. VR is used in many ways to create real life situations to better equip people for certain jobs that require specific skills. TEL (Technology-enhanced learning) caters toward specific learning goals to help develop higher-order skills, and this, combined with computer science, the researchers believe will create more efficient learning. In the study, a group of students had to assemble an industrial plug, once with paper instructions, once with AR (a

QR code would lead to a floating example that walked the students through the instructions), and once with a VR headset that allowed the students to put it together virtually with virtual instructions (the students were trained prior on how to operate the VR headset). Based on the results, using VR saves time (Gabajová et al., 2019).

Intended outcomes: The study's main goal was to find out how the implementation of new technologies, specifically VR and AR, could reduce time in a construction assembly line (assembling an industrial plug). This new technology will improve the process of acquiring skills, especially in critical thinking. The benefit of the VR training is that it allows the new employees to teach themselves so other, more experienced employees can do their needed work instead of monitoring the new guy. It allows for testing/training virtually first before making any costly/drastic physical changes or mistakes. It saves money and time. The disadvantage is that older generations have more trouble learning the evolving technologies. Overall, the new technologies would create a more efficient training pipeline (Gabajová et al., 2019).

Technology 1.8. Extended Reality (XR) in a business school setting

User Interaction: Traditional teaching methods offer students a cognitive understanding of sustainability issues but tend to lack the holistic point of view several scholars advocate. This article is based on the need to add training on specific skills, reorienting management education to engage with wicked problems through increasingly creative, open, and iterative processes that invite reflection and meaningful redesign. This shift in problem-solving approaches is particularly relevant to complex environmental and social issues such as climate change and persistent poverty. Despite the critical need to engage with such problems, many business schools continue to rely upon the traditional rational-analytical approach in their curricula, leaving students—and future managers—ill-equipped for answering challenges that require new ways of problem-solving. The proposed idea is experiential learning using design thinking. This would facilitate solving problems using empathy, reframing, prototyping, experimentation, testing, and redesign (Andrew et al., 2020).

The use of new technologies like XR could help students develop a more holistic understanding of the problem at hand and allow them to iterate different solutions quickly and in a more cost-effective way. In addition to the compelling case made for expanding the breadth of sustainability-related learning (in terms of stakeholders, time, and disciplines), scholars have also advocated for increasing the depth of engagement with these challenges (Andrew et al., 2020).

Intended Outcomes: XR provides a platform that can amplify empathy, facilitate reframing, shorten design iteration cycles, compress extended time frames, span physical space, and limit downside risks of experimentation by novices (i.e., students); all things that tend to bedevil sustainability education delivered by other methods. The goal of the study was to create an integrative conceptual model that provides guidance for educators engaging with the complex, transdisciplinary, spatially-dispersed, and otherwise wicked problems inherent in sustainability-related challenges using XRtechnologies. Overall, the XR will allow students to get a shaped education through understanding risk management, the design thinking process, and see different stakeholder perspectives (Andrew et al., 2020).

Virtual Reality

Technology 2.1. "Augmented Reality as a Sustainable Technology to Improve Academic Achievement in Students with and without Special Educational Needs"

User interaction: Researchers conducted a pre-experimental study with Chilean high school students, in which students used AR and VR to learn chemistry topics. 60 female participants received pre, post, and follow-up assessments before, after, and a month after undergoing a group learning plan heavily reliant on AR and VR technologies. The students built and manipulated 3D models of compounds using the AR VR Molecules Editor application instead of traditional physical models for teaching molecule structure. They received three 45-minute sessions with the technology, each session with its corresponding activity where the students were either creating, modifying, or identifying molecules and their structure. Students worked in groups of 3-5. (Badilla-Quintana et al., 2020)

Intended outcomes: Researchers wanted to discern whether or not using AR is predictive of improvements in academic achievement and knowledge retention as well as the levels of acceptance and motivation of students surrounding AR. Researchers concluded there is strong evidence AR can improve learning outcomes and retention, as students scored significantly better on their post and follow-up assessments. AR was seen to be a more successful educational tool relative to traditional methods, such as the aforementioned physical models, but it was shown to improve student motivation and enthusiasm. (Badilla-Quintana et al., 2020)

Technology 2.2. VR in a classroom setting

User Interaction: A study was done in Miami, FL, to promote sustainability through virtual reality. The primary objective of this case study was to use a user-centered design (UCD) process to create a virtual reality (VR) educational experience that could instill empathy and encourage behavior change concerning climate change in an American city. Students would use VR technology to personally experience stories from around the globe regarding climate change to help them understand the severity of the situation. This type of emerging technology is becoming more commonly used because of its ability to motivate students and simulate real world experiences. Students would use the VR equipment to learn about global warming and work through solutions (Posluszny et al., 2020).

Intended Outcomes: The study was based on information gathered through literature reviews, interviews with professors who teach about sustainability and also college students, focus groups, and design activities. Research showed that students want to help but don't know how and that seeing the effects on a city close to their home had a significant impact on their intention to help. Storytelling for sustainability creates affordances for users to build social capital and contribute to sustainability conversations by challenging assumptions, creating awareness, and becoming agents of social change. If the VR experience they designed shows how life could look on American soil 50 years into the future, then it is possible that it could spark a behavioral change (Posluszny et al., 2020).

Technology 2.3. VR in a classroom setting

for hands-on learning

User Interaction: Salah et al. (2019) posit that VR can create a new hands-on learning method. VR (headset) can help create complex problems and scenarios the students can work through, make mistakes, and learn. Such an approach can also allow students to teach others (through partner work, presentations, etc.). It could effectively promote learning through teaching (sparks interest in the subject matter), where students can learn to work in teams and individually (Salah et al., 2019).

Intended Outcomes: The goal of using VR in the classroom is to prevent workplace mistakes and close the gap between educational knowledge and practical application. VR can also create a more realistic understanding of a workplace setting to better prepare students with necessary professional skills. It could allow students to become comfortable with more delicate and experimental technologies, experience possible real life situations, and prepare them for the workplace. VR can be a solution to allow students to deal with real-life situations in a classroom setting where that is not always possible (Salah et al., 2019).

Technology 2.4. The Influences of the 2D Image-Based Augmented Reality and Virtual Reality on Student Learning

User Interaction: This is a 2016 study from Taiwan to compare the influence of 2D image-based VR and AR in terms of learning achievement and task performance in an inquiry-based astronomy course. In the course, two systems were employed: (VR) Sky Map and (AR) Moon Finder, both simulation systems on a handheld device that allow users to set different dates and times for displaying the moon. Since it was an inquiry-based teaching method, both systems were installed in tablet PCs that provide situational data. In brief, the VR option supports the development of scientific understanding by making students focus on virtual celestial bodies, whereas the AR helps students link virtual elements to real life environments. (Liou et al., 2017)

Intended Outcomes: With the features of the AR system, learners can easily integrate virtual objects and natural environments and ultimately decrease mental load to improve learning. The sense of immediacy in the AR group was higher than in the VR group, improving the students' positive learning experience and concentration. (Liou et al., 2017)

Internet of Things

Technology 3.1. IoT Environmental Monitoring Systems

User Interaction: The GAIA Project, an H2020-funded research group, equips students with a lab kit that consists of various IoT devices, sensors, actuators, and other hardware components (LEDs, resistors, etc.) that can be used to make custom circuits that collect real-time data on energy consumption, lighting, heating, thermal comfort and energy efficiency. Students first brainstorm potential solutions to environmental problems at their school, mock-up and assemble their circuits, and write code that can connect their devices to the cloud to gather data in real-time. Finally, students can analyze patterns and trends in their data with visualization software. Once conclusions are made about the data, students can take action within their school to improve sustainability practices (Mylonas et al., 2021).

Intended Outcomes: As a result of its data-driven methodology and hands-on approach, students are expected to be more engaged with learning about sustainability, particularly because it may directly impact their school's sustainability practices. GAIA (*Green Awareness in Action)*, an H2020-funded research group, intends to introduce engineering, coding, and electronics within the context of sustainability to promote the idea that engineering and the environment are not necessarily at odds when students, like them, make informed, data-driven and environmentally-conscious decisions (Mylonas et al., 2021).

Technology 3.2. Low-Cost Arduino Environmental Monitors

User Interaction: Students work together with the support of educators to assemble small environmental monitors with Arduinos, sensors, and other circuitry/hardware. In addition to having a role in the execution, students have a choice in the design and aim of the project (Alo et al., 2020).

Intended Outcomes: The project, *Ecoinformática para Jóvenes*, or *Ecoinformatics for children*, intends to change students' perspectives on STEM education. Most students in a pre-workshop survey noted fear of the abstract nature and complexity of certain STEM subjects and a fear of the environmental impact of engineering. This project thus aims to help students become more enthusiastic about STEM subjects and knowledgeable about the environment through real-world applications (sustainability, anthropization, climate change) and project-based, constructivist learning (Alo et al., 2020).

Discussion

How and in what ways do physical interactions with emerging technologies engage learners in learning about sustainability topics?

Physical interactions with emerging learning technologies can engage learners by helping visualize phenomena, creating immersive firsthand experiences, developing holistic (system-wide) understanding of phenomena, quickly iterating upon solutions in low-cost ways, providing learners with a broader array of sensory information, and supporting thinking through possible solutions more critically before building them. As with most novel technologies, some learners may be motivated to learn about sustainability topics because they are curious about engaging with emerging technologies.

In the case of physical phenomena such as flood and drought conditions or waste, technology like AR and VR can allow better visualization and help students generate more lasting and realistic understandings. Learning is often more immersive, wherein learners can experience things they're learning firsthand, which could increase retention, understanding, and enthusiasm. The use of new technologies like XR could help students develop a more holistic understanding of the problem at hand and allow them to iterate different solutions quickly and in a more cost-effective way. The broader range of sensory information provided by emerging technologies can enable students to interact with information in the best way they see fit. Communication is more personable to students' needs and preferences. Learners have the opportunity to learn about technology as a producer/developer as opposed to a consumer. They can be encouraged to be creative, think not only about *what* they are creating but *why* it should be created and what impact it will have in improving their environment.

How do the mental models developed as a result of such interactions impact learners' understanding of sustainability topics?

Mental models developed as a result of engaging with emerging learning technologies can impact learners' understanding of sustainability topics by blurring disciplinary boundaries between the technical and the social, by making learning experiences more intimate and relevant for learners, by providing a venue for low-stakes design and implementation of solutions, and by invoking feelings of empathy, urgency, and personal connection. Access to learning and technology often hampers technology-aided learning, and technologies like AR and IoT prove to be fairly accessible financially since they can be accessed from mobile phones.

These technologies and their applications often blur the boundaries between the humanities, sciences, and social sciences, leading to more holistic and universally applicable mental models of sustainability topics. Learners no longer view sustainability topics as solely scientific and are instead encouraged to consider them in non-traditional ways. Immersive technologies such as AR and VR can also be made to be more intimate than traditional teaching mediums. Students can potentially feel more empowered when using emerging technologies to quickly model and create impactful engineering solutions. XR technologies can combine emotive, hands-on learning with facts and statistics to help students *empathize* more with the subject matter and feel a greater sense of urgency and concern. Finally, a good education is only as good as how accessible it is, and AR and IoT have the potential to make good technology-supported learning accessible.

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