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A systematic literature review to identify evidence-based principles to improve online environmental education

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ABSTRACT
Many environmental educators shifted to online programs in the midst of the COVID-19 pandemic. We conducted a systematic literature review to identify program characteristics from digital environmental education experiences that are associated with one or more elements of environmental literacy. After reviewing 153 candidate articles, 32 articles that evaluated 47 diverse programs met our selection criteria. For each of these programs, we systematically coded the articles to identify guiding theories, program types, program characteristics, and outcomes assessed. We also identified the authors' explanations and empirical evidence for program characteristics that led to positive outcomes. In this paper, we synthesize the results and present 12 guiding principles that show promise in enhancing outcomes related to environmental literacy in online programs for K-12 students. These principles, which are defined and illustrated with examples from the literature, include: social-ecological connections, relevance, social interactions, role models, autonomy, active involvement, challenge, use of multiple modalities, positive framing, preparation, feedback and reflection.

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Introduction

The global COVID-19 pandemic spurred many organizations that provide environmental education (EE) for youth to shift from field trips and other live interactions to online activities. While some organizations were already engaged in this type of program delivery, many environmental educators are largely starting from scratch—rapidly learning new technologies, and designing and leading online programs without much guidance about what works best. We conducted a systematic literature review of empirical research on digital EE programs published between 2010 and 2020 to identify lessons regarding promising approaches for designing and delivering effective online EE.

EE programs often strive to enhance aspects of environmental literacy in program participants. Environmental literacy encompasses a broad array of outcomes, including improved knowledge and understanding of various environmental concepts and issues; cognitive and affective dispositions such as environmental attitudes, self-efficacy and interest in learning; skills such as critical thinking, communication and collaboration; and enactment of environmentally responsible

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behaviors such as consumer and conservation actions or civic engagement (Hollweg et al. 2011; Powell et al. 2019). *Online* EE programs are programs that include components that are connected to or available through technology such as computers, personal devices and/or the Internet, and are designed to improve any environmental literacy outcomes. These programs may include digital videos, electronic field trips, simulations or games, virtual environments or online activities. They may be synchronous (in real-time), or asynchronous (not at the same time), or a combination of both (hybrid or blended). Some educators used online EE prior to the pandemic, often from their classrooms or informal learning settings, to supplement field-based programs. However, the proliferation of new programs and technology (e.g. Zoom breakout rooms and online chat features) has sparked more interest in both research and design of online EE programs (Quay et al. 2020).

There are several compelling reasons why virtual EE programs should continue post-pandemic. For example, online EE and other forms of digital learning, if effective, can expand the reach of EE to audiences who do not have access to live programs because of financial, geographical or physical constraints. Online activities can also enhance future field trips by providing effective pre-experience preparation and post-visit follow-up activities, each of which have been shown to enhance positive outcomes for participants (Lee, Stern, and Powell 2020; Smith-Sebasto and Cavern 2006).) Thus, identifying which approaches are the most promising for enhancing outcomes will improve EE programs now and into the future.

We have been unable to locate any existing systematic literature review focusing on online practices related to environmental literacy outcomes. We conducted such a review, using methods established by (Stern, Powell, and Hill 2014) and employed by others (e.g. Ardoin, Bowers, and Gaillard 2020) to systematically gather and interpret empirical evidence that can provide useful guidance for the field now and into the future.

Methods

Article selection

Our goal was to find all empirical articles published between 2010 and 2020 that assessed digital learning activities in the fields of environmental and STEM education for K-12 students at home, school or at an informal learning setting and that measured at least one outcome associated with environmental literacy. We began by reviewing mainstream EE and technology education journals to identify those which included articles or topics related to our work. We selected the following list of journals based on their scope and reviewed the table of contents for relevant articles published between 2010 and April of 2020:*Journal of Experiential Education, Journal of Environmental Education, Environmental Education Research, Journal of Interpretation Research, Canadian Journal of Environmental Education, Environmental Communication, Australian Journal of Environmental Education, Applied Environmental Education and Communication, Journal of Science Education and Technology, Computers and Education, Tech Trends, Journal of Geoscience Education*, and *Journal of Biological Education*. We then conducted keyword searches in Web of Science and EBSCO databases. We used the following search terms: virtual + "field trip," virtual + "environmental education," online + "environmental education," online + "field trip," digital + "field trip," digital + "environmental education." We identified 370 titles with potential relevance to our work. We used the following inclusion criteria for our study:

1. The programs served K-12 audiences.
2. At least one environmental literacy-related outcome was measured empirically after program participation.

3. The program/activity was conducted through a digital interface either online or in a classroom environment.
4. The program description included sufficient information to identify program characteristics that may influence program outcomes.
5. Technology utilized was readily available in most schools (e.g. programs that could be accessed from computers, mobile devices or large screens were included, and immersive VR programs that required headsets were excluded).

We narrowed from 370 to 123 titles after reading abstracts. Often, the abstracts did not provide enough information to determine whether the article was relevant to our study. The first author reviewed these 123 articles, and eliminated those that did not meet our criteria. Thirty relevant articles were identified through this process. As a final step, the first author reviewed reference sections and citations in Google Scholar for each of the 30 articles, yielding two additional relevant articles. Of the 32 final articles, some researched two or three distinct programs or audiences, yielding a total of 47 programs that were analyzed.

Article coding and analysis

Program types and characteristics, measured outcomes, and theories were identified and categorized using inductive and deductive methods. The team met to create an initial list of program types, characteristic, and approaches; outcomes; and theories from the field of environmental education, formal education, interpretation and other similar fields that were relevant to digital EE programs. We included many practices that were identified in a prior literature review focused on consensus-based best practices in environmental education (Stern et al. 2014). This list of initial codes included practices such as active participation, reflection and place-based learning. Definitions were created for each code, based on prior work. Next, we each individually coded two articles and, following discussion, came to consensus on program characteristics and outcomes for each article. As we continued to code articles, we added new program characteristics, technology tools, theories, and outcomes that emerged from the data. We also made notes about which features of programs had empirical evidence linking them to outcomes. This evidence included variables that were isolated through quantitative analyses and found to be significant predictors of an outcome, or program characteristics identified by study participants as important (in interviews, surveys, focus groups, etc.). Finally, we reviewed each article's discussion section, and documented authors' claims about program characteristics that may have led to measured outcomes.

Following the methodology used in prior work (Stern et al. 2014), outcomes were coded as null/negative, mixed, or positive. These codes were assigned differently in quantitative and qualitative studies. In quantitative studies, null or negative findings occurred where the authors reported no significant positive results, or significant negative results for that outcome. Mixed findings were reported when some outcomes were positive and others were null or negative, based on statistical tests. Positive outcomes were coded when all measures of an outcome exhibited statistically significant positive results, or positive outcomes were reported for at least 50% of participants. In studies that used only qualitative methods, only mixed or positive results were reported. In these qualitative studies, outcomes were reported as mixed when authors reported that some students showed evidence of positive outcomes while others did not. Outcomes were coded as positive when authors of qualitative studies reported only positive results for that outcome.

At least two members of the research team read each article; the lead author read all of the articles and compared and discussed coding with each reviewer. Two full team discussions resulted in the final coding scheme and resolution of any disputed coding between original coding pairs. The final list of codes that were most prevalent and salient are listed and defined in Tables 1–4.

Table 1. Guiding theories reported by authors of the reviewed manuscripts.

Theory (authors)	Description	Authors referencing this theory
Self-determination theory (Deci and Ryan 1985; Ryan and Deci 2000)	Learning contexts that fulfill three fundamental needs lead to intrinsic motivation, positive emotion and enhanced performance. These needs are: • competence- a feeling of capability or self-efficacy • autonomy – a feeling of control or ability to make decisions • relatedness – a feeling of connection or belonging to a group	Sammet, Kutta, and Dreesmann 2015; Schönfelder and Bogner 2017; Tutwiler, Lin, and Chang 2013
Constructivism (Jacobson, McDuff, and Monroe 2015; Piaget 1952; Vygotsky 1962)	Learners actively construct their own understandings through building upon their prior knowledge and/or actively engaging in real-world experiences.	Adedokun et al. 2015; Fokides and Chachlaki 2020; Pedersen and Irby 2014; Sammet, Kutta, and Dreesmann 2015
Cognitive theory of multimedia learning (Mayer 2005, 2014)	"A theory of how people learn from words and pictures, based on the idea that people possess separate channels for processing verbal and visual material (dual-channel assumption), each channel can process only a small amount of material at a time (limited-capacity assumption), and meaningful learning involves engaging in appropriate cognitive processing during learning (active processing assumption)" (Mayer 2014, 67)	Salmeron et al. 2020
Sociocultural learning theory (Vygotsky 1980)	Learning emerges through interactions with other people and cultural tools/artifacts; the selection of tools and artifacts along with questions that guide discussions influence the depth and direction of learning.	Edstrand 2016; Fauville 2017
Situated learning theory (Brown, Collins, and Duguid 1989; Lave 1988; Lave and Wenger 1991)	Learning always occurs in a specific context, and knowledge is "in part a product of the activity, context, and culture in which it is developed and used" (Brown, Collins, and Duguid 1989, 32)	Edstrand 2016; Fokides and Chachlaki 2020; Pedersen and Irby 2014; Tarng et al. 2010
Shallowing hypothesis (Annisette and Lafreniere 2017)	The shallowing hypothesis suggests that most of our current interactions with digital media are quick episodes driven by immediate rewards (e.g. number of "likes" in response to an uploaded Instagram video) (Annisette and Lafreniere 2017 in Salmeron et al. 2020). Therefore, understanding complex information in digital form can be challenging since students need to focus in order to construct a coherent representation of the message displayed (Salmeron et al. 2020).	Salmeron et al. 2020

After reading, coding and tabulating results from the articles, we deliberated as a team, guided by theory and prior literature, to synthesize the results regarding the most promising program approaches and characteristics. This process led to the development of 12 overarching guiding principles (Table 5). Each of the four research team members brought their knowledge of different bodies of literature and experience from work in the field of environmental education as a lens throughout this process.

Results

The results are drawn from a systematic review of 32 articles that evaluated 47 distinct programs published between 2010 and 2020.

Study locations and audience description

Fourteen of the studies focused on 26 programs occurring in the United States. Other studies focused on programs in Germany (3), Greece (2), Taiwan (2), Sweden (2), New Zealand, Israel,

Table 2. Program categories utilized in studies.

Category	Definition	Studies included
Electronic Field Trip	A human in the real world introduces students virtually to "places, topics and ways of working that they might not otherwise experience" (Loizzo et al. 2019)	Adedokun et al. 2015; Bruch, Braun, and Teel 2011; Chang-Rundgren et al. 2015; Delacruz 2019;
Virtual Environment	Three-dimensional representations of a place that allow users to "move around," interacting with objects within the environment. (Pederson and Irby 2014)	Barbailos et al. 2013; Bruni et al. 2017; Chang et al. 2020; Fauville 2017; Fokides and Chachlaki 2020; Grotzer et al. 2013; Han 2020; Harrington 2011; Mead et al. 2019; Pedersen and Irby 2014; Petersson, Lantz-Andersson, and Saljö 2013; Puhek, Perše, and Šorgo 2012; Tarng et al. 2010; Tutwiler, Lin, and Chang 2013
Pre-recorded Videos	An educational video recorded in advance	Chen and Cowie 2014; Kleinhenz and Parker 2017; Klingenberg 2014; Salmeron et al. 2020; Sammet, Kutta, and Dreesmann 2015; Zydney and Grincewicz 2011
Web-based Activities	Online educational materials designed to engage students in learning	Barak and Ziv 2013; Bruni et al. 2017; Cohn et al. 2014; Edstrand 2016; Fauville 2017; Gill, Marcum-Dietrich, and Becker-Klein 2014; Hartley et al. 2018; Petersson, Lantz-Andersson, and Saljö 2013; Salmeron et al. 2020; Schonfelder and Bogner 2017, 2018;
Simulations	Approximate imitation of a process or system	Barbailos et al., 2013; Bruni et al. 2017; Chang et al. 2020; Fauville 2017; Fokides and Chachlaki 2020; Gill, Marcum-Dietrich, and Becker-Klein 2014; Grotzer et al. 2013; Harrington 2011, 2012; Pedersen and Irby 2014; Petersson, Lantz-Andersson, and Saljö 2013; Puhek, Perše, and Šorgo 2012; Tarng et al. 2010; Tutwiler, Lin, and Chang 2013; Zydney and Grincewicz 2011
Synchronous Experience	A real-time activity guided by an educator	Adedokun et al. 2015; Bruch, Braun, and Teel 2011

Table 3 . Outcomes related to environmental literacy assessed in online programs.

Outcome and definition	# programs	Null	Mixed	Positive
Knowledge - individual participants' change in knowledge of the subject after exposure to EE	35		6%	94%
Interest- a psychological state that in later phases of development is also a predisposition to reengage particular content over time	12		17%	83%
Environmental attitudes - individual participants' change in feelings toward the environment or environmental actions related to the programming (encompasses feelings of concern)	11	27%	9%	64%
Environmental awareness - individual participants' change in recognition or cognizance of environmental issues or concepts	10			100%
Skills - individual participants' change in abilities to perform a particular action	7		14%	86%
Critical thinking - demonstration of thinking that moves beyond comprehension and analysis toward inference, explanation, and application	7		14%	86%
Enjoyment - individual participants' overall satisfaction or enjoyment levels associated with the educational experience.	6			100%
Attitudes toward science/scientists - students show change in beliefs/ feelings about science/scientists	4			100%
Desire to visit -students communicate motivation/ interest in visiting the site featured in the program.	4		25%	75%
Intentions -individual participants' self-reported intent to change a behavior or take action	2		50%	50%
Behavior- individual participants' self-reported behavior changes following EE program or activity	1			100%
Self-efficacy - an individual's belief in their ability to succeed	1			100%

Table 4. Program characteristics and pedagogies associated with environmental literacy outcomes.

Guiding Principle	Program Characteristic	Definition	# Of programs	% Null or -	% Mixed	% +	**Empirical evidence**/Authors attribution
1. Social-ecological connections	Social-ecological connections	The program focuses on relationships between people and ecological systems - e.g. human impacts on ecosystems and interdependence	27		26%	74%	Barbailos et al. 2013; Cohn et al. 2014; Edstrand 2016; **Tarng et al.** 2010
	Place-based	Situated in an actual location and designed to deepen participants' connection to that place	20	15%	10%	75%	**Chen and Cowie** 2014**; Cohn et al.** 2014**; Delacruz** 2019**; Gill, Marcum-Dietrich, and Becker-Klein** 2014
	Multiple perspectives	Explicitly acknowledges different views or looks at an issue with two or more (e.g. political, cultural, economic, social or environmental) lenses	14		21%	79%	Chen and Cowie 2014**;** Gill, Marcum-Dietrich, and Becker-Klein 2014; **Zydney and Grincewicz** 2011
2. Relevance	Use of real-world data	Program includes the use of real-world data by instructors or students.	15		13%	87%	**Cohn et al.** 2014**; Edstrand** 2016
	Cultural component	Program includes an explicit connection to or element focused on one or more cultures.	7		14%	86%	Cohn et al. 2014; **Delacruz** 2019**; Edstrand** 2016
	Relevance to students' lives	Lesson content references or makes explicit connections to the students' lives or interests outside of school	14		14%	86%	**Zydney and Grincewicz** 2011**; Chen and Cowie** 2014
	Use of stories	A story is used to illustrate an idea or connect with the audience	8		25%	75%	**Chen and Cowie** 2014
	Societal relevance	Program addresses or connects explicitly to a topic, issue or policy of current relevance to society (e.g. climate change, Endangered Species act, water quality)	23		26%	74%	**Chen and Cowie** 2014**; Edstrand** 2016
	Fact-focused	Program focuses primarily on conveying facts and information	3	33%	67%		
3. Social interactions	Social engagement	Students have an opportunity to interact with others (peers, instructors) reciprocally.	11		11%	89%	**Barak and Ziv** 2013**; Delacruz** 2019**; Han** 2020**;** Fauville 2017; Fokides and Chachlaki 2020
	Collaborative learning/ group work	Students have an opportunity to work with others on a task.	9		22%	78%	**Barak and Ziv** 2013**;** Delacruz 2019; Fokides and Chachlaki 2020; Tutwiler, Lin, and Chang 2013
4. Role models	Career Pathways	Description of a specific career including the type of work.	11			100%	**Chen and Cowie** 2014**; Mead et al.** 2019
	Content area Specialist	An expert in a specific field shares knowledge or models thinking or behaviors for students	19		11%	89%	**Chen and Cowie** 2014**;** Mead et al. 2019**; Salmeron et al.** 2020**;** Fauville 2017; Kleinhenz and Parker 2017

(Continued)

Table 4. (Continued)

5. Autonomy	Autonomy-high	Students have full freedom to direct learning and move and explore	14		21%	79%	**Barak and Ziv** 2013**;** Fokides and Chachlaki 2020; **Harrington** 2012**; Tarng et al.** 2010**; Tutwiler, Lin, and Chang** 2013
	Autonomy-moderate	Students have some independence regarding directing learning but choices are constrained/limited	9		11%	89%	**Bruni et al.** 2017**; Cohn et al.** 2014**;** Delacruz 2019; **Gill et al.**
	Autonomy-low	Students have no freedom or choices, passively watching and following procedures	17	6%	35%	59%	
6. Active involvement	Student-Navigated Technology	Students work individually or in small groups on an electronic device rather than observing one screen together throughout the lesson	33	3%	24%	73%	**Gill, Marcum-Dietrich, and Becker-Klein** 2014**;** Mead et al. 2019; **Tutwiler, Lin, and Chang** 2013
	Student-designed products	Students design and upload a digital artifact to post/share with others (art, videos, essays- does not include just discussion/ comments)	6			100%	**Barak and Ziv** 2013**; Delacruz** 2019
7.Challenge	Problem-based	Focused on promoting understanding of a specific social-ecological problem and identifying potential solutions	6			100%	Gill, Marcum-Dietrich, and Becker-Klein 2014; Fokides and Chachlaki 2020; Zydney and Grincewicz 2011
	Inquiry-oriented	Using a guiding, open-ended question as a central part of an activity	18		11%	89%	Mead et al. 2019; Pederson and Irby 2014; Zydney and Grincewicz 2011
8. Multiple modalities	Changes over time	Students are able to observe changes in organisms, populations or landscapes through the use of digital images, videos, data or simulation.	17		35%	65%	Barbailos et al. 2013; Chang-Rundgren et al. 2015; **Cohn et al.** 2014**; Gill, Marcum-Dietrich, and Becker-Klein** 2014
	Geographic orientation	Static or interactive maps were used in the program to help increase geographic awareness and sense of place	10		10%	90%	**Cohn et al.** 2014
9. Positive framing	Positive framing	Content emphasizes how people/communities can affect meaningful positive change	7		17%	83%	**Chen and Cowie** 2014**;** Kleinhenz and Parker 2017
	Action orientation	Program focuses on one or more specific action that students can/should do (i.e. socially acceptable environmental behavior)	6		33%	67%	Hartley et al. 2018
10. Preparation	Pre-activity	Program includes pre-activities to complete prior to video or field trip	13		8%	92%	Cohn et al. 2014; **Harrington** 2011
11. Feedback	Feedback through interactive technology	Direct feedback on students' actions or ideas is built into the technical design of the program	7		29%	71%	Barbailos et al. 2013; Chang et al. 2020; Mead et al. 2019; **Tarng et al.** 2010
	Feedback from instructor or peers	Student receives responses about their performance or understanding from instructor or peers	2			100%	Barak and Ziv 2013; Fauville 2017
12. Reflection	Reflection on learning	Explicit opportunities for students to reflect upon the experience and integrate concepts	8		38%	62%	Edstrand 2016; Fauville 2017; **Han** 2020**;** Zydney and Grincewicz 2011

Table 5. Guiding principles for the development of online EE programs.

	Fostering Connections
1. Social-ecological connections	Focus on the connections between people and the ecological systems that surround them. Build awareness or draw attention to changes in organisms, populations or landscapes through the use of digital images, videos, data representations or simulations. Topics may include: • relationships between people and the natural world • interdependence • human impacts on ecosystems (positive and negative) • causes of environmental problems and effects on society and natural systems
2. Relevance	Choose topics or issues that: • Make personal connections with participants • Matter to local communities and cultural groups • Focus on issues or policies that are the subject of current discourse (locally, nationally or internationally)
3. Social interactions	Opportunities to interact with peers and educators through two-way communication (either synchronously or asynchronously) • through group work • through discussions • asking and answering questions
4. Role models	Authentic characters teach about a topic, place or career through stories that make personal connections and with tangible examples and evidence. • share knowledge and experiences • model skills or behaviors • choose diverse role models to help participants imagine themselves in the roles portrayed by the instructors.
	Supporting Learner Agency
5. Autonomy	Allow students to: • make choices regarding what they are interested in learning or doing • direct their own learning experience • share their knowledge and utilize skills in different ways
6. Active involvement	Participants are not just passive recipients of information, but rather are prompted to engage with (or actively manipulate) materials or ideas. This may include: • completing an independent task or activity • developing models or analyzing data • creating products such as nature journal pages or drawings
7. Challenge	Provide content that builds on and extends learning beyond factual recall and requires higher cognitive processes. • design activities that require application, drawing connections among ideas, justifying claims with evidence, problem-solving, or generating ideas or solutions.
8. Use of multiple modalities	Optimize learning and make content accessible by selecting and combining different modalities (audio, visual and/or kinesthetic) for different purposes. • Voices can convey stories through conversations, explain ideas or persuade by sharing evidence and data • Models and diagrams can be enhanced with simple printed text and oral explanations • Videos, photos and maps can orient students to people and places • Physical activities allow them to learn kinesthetically
9. Positive framing	Emphasize the potential for positive solutions or outcomes. • draw attention to what can/has/might be accomplished through individual or collective efforts • share stories and examples of actions taken by others that had a positive impact
	Completing the Experiential Learning Cycle
10. Preparation	Consider what skills or background knowledge students need at the start of a program.Add pre-activities or modules to prepare them for success • Teach them background knowledge and/or how to utilize technology so they can fully participate in learning activities
11. Feedback	Participants receive feedback on technical skills, understanding of concepts or performance in the midst of learning. Feedback can come from many sources… • Peer feedback • Educator feedback • Feedback embedded in technology
12. Reflection	Provide explicit opportunities for students to reflect upon the learning experience and integrate concepts. • Reflection can occur during or after a program • Can occur through discussion, writing, kinesthetic tasks or creating visual representations • Open-ended questions are useful in eliciting meaningful reflection

Slovenia, Costa Rica, Ecuador and Spain. Ten of the studies included students in grade K-6; 17 of the studies included students in grades 7-12; and five studies focused on programs for both age groups.

Methods used

Nineteen of the studies employed quantitative methods, nine were mixed-methods studies, and four were qualitative. Twenty-one of the studies were quasi-experimental designs that included a pre-and post-test. Fourteen studies used a comparison group, and four had a control group.

Theories that guided research and design

Table 1 summarizes key theories authors described as guiding their approaches. Theories that were mentioned briefly or only utilized in one study were not included in this table. These theories guided our thinking as we summarized results and organized program characteristics into principles.

Program types

We categorized programs into six broad program types (Table 2); some programs were categorized into more than one type. Nineteen of the programs included web-based activities, such as virtual laboratory experiments, carbon footprint calculators, and collecting data from a virtual beehive. Fourteen programs studied virtual environments, and four investigated electronic field trips to parks and other specific geographic locations. Virtual environments are three-dimensional representations of a space (either real or imagined), allowing users to interact with objects within that space (Pedersen and Irby 2014). Fifteen programs included simulations such as modeling activities, including where students made farming decisions about irrigation that impacted the broader ecosystem and water levels in a nearby lake (Barbalios et al. 2013). Six programs used pre-recorded videos. Only two of the 47 programs were entirely synchronous (performed in real-time). Some programs fit into multiple categories. For example, the zipTrips programs described by Adedokun et al. (2015) included a 45-minute synchronous interactive electronic field trip that allowed students to learn about scientists and their work, and also included additional online videos and lesson plans for teachers. Thus, this program was coded into multiple categories, including electronic field trip, synchronous program, and pre-recorded videos.

Outcomes

Table 3 summarizes the outcomes associated with environmental literacy that were assessed and the number of studies that reported positive, mixed, and null/negative findings for each outcome. Knowledge was the outcome assessed most often. A variety of cognitive and affective dispositions were assessed: environmental attitudes, self-efficacy, awareness, enjoyment, and interest in learning. Skills assessed included critical thinking, asking questions, scientific reasoning, scientific investigation, analyzing and interpreting data, considering different perspectives and inquiry skills. Environmental intentions and environmentally responsible behaviors were assessed infrequently relative to other outcomes.

Program characteristics and their association with outcomes

Across all of the 32 articles, 28 influential program characteristics emerged, which we classified into 12 overarching guiding principles (Table 4). The column at the far right of Table 4 indicates the articles in which specific program characteristics were empirically isolated or mentioned as important by the authors. Programmatic approaches and characteristics that were associated with positive outcomes more than 75% of the time included: career pathways and content area specialists, multiple perspectives, social engagement and collaborative learning, use of real-world data, cultural component, place-based, use of stories, moderate or high autonomy, student-designed products or assignments, positive framing, inquiry-oriented, problem-based, geographic orientation, pre-activity and feedback from instructors or peers. Fact-focused and low autonomy programs were more commonly associated with less positive outcomes than other program characteristics.

From characteristics to principles

We identified 12 guiding principles based on a synthesis of the 28 influential program characteristics and organized them into three broad categories: (1) fostering connections; (2) supporting learner agency; and (3) completing the experiential learning cycle. Our categorization is based within a constructivist paradigm, which acknowledges that learners are active participants in knowledge creation rather than passive recipients of transmitted knowledge (Piaget 1952; Vygotsky 1962). The first two categories are supported by the theories shared in Table 1. The third category also draws on Kolb's (1984) experiential learning cycle, which situates the concrete learning experience within a broader cycle of preparation, reflection, and application. Each of these broad categories and the practices they contain are mutually reinforcing.

Fostering connections

Fostering connections principles below (principles 1-4) reflect key themes from the field of interpretation as well as self-determination theory and sociocultural learning theory. Interpretation stresses the importance of creating emotional and intellectual connections to the content of a program (Stern et al. 2013); self-determination theory and sociocultural learning theory stress the role of social relationships in learning (Deci and Ryan 1985; Vygotsky 1980). Programs that convey the relevance of feedback loops between social and natural systems help students to forge connections with content, while social interactions and including role models can enhance social connections and feelings of relatedness.

Principle #1- Social-ecological connections. Many programs introduced students to social-ecological issues, emphasizing the feedback loops between social and natural systems (e.g. Barbailos et al. 2013; Edstrand 2016; Fokides and Chachlaki 2020; Zydney and Grincewicz 2011). These programs often used photos, videos and other forms of data to illustrate social-ecological connections, enabling students to observe places and organisms across temporal and spatial scales and to discern changes (Sagarin and Pauchard 2012). Photos, videos, and other visual aids, coupled with guiding questions, can help students consider cause and effect relationships. Simulations or virtual investigations were also utilized. For example, the Acid Ocean Virtual Lab modeled changes in sea urchin larvae growth in water with varying pH levels (Petersson, Lantz-Andersson, and Saljö 2013). The "Model my Watershed" app with accompanying lessons simulated how different land use decisions influence local watershed conditions (Gill, Marcum-Dietrich, and Becker-Klein 2014). Increasing awareness about the coupled nature of social and ecological systems may help students to understand how their decisions about resource use impact resources and how they can play active roles in improving these systems.

Principle #2- Relevance. Programs can improve the relevance to participants in a variety of ways: by making personal connections to their lived experiences, focusing on issues that matter to members of the audience, and enhancing understanding of cultural perspectives. In one program, three educators worked with their K-4 students ($n = 58$) in Costa Rica, Ohio and Ecuador to develop and share school-based virtual field trips for other classes (Delacruz 2019). Students were asked to consider: What would you want other students at another school to know about your school, classrooms and yourselves? This question allowed them to choose content that was personally relevant to students and their international audiences. Students used photographs, audio and video recordings to teach others about their schools and communities, building cultural competence. Culturally relevant content and pedagogy may be particularly important for historically marginalized students (Ladson-Billings 1995). Practices that align with and affirm students' cultural identities and foster critical social engagement have also been found to be particularly beneficial for at-risk youth and underserved-audiences (Dee and Penner 2017; Gay 2010; Bang and Medin 2010). Fact based programs focused on conveying a lot of scientific information without contextualization may not feel relevant to students.

Principle #3- Social interactions. Learning occurs through interactions with other people (Vygotsky 1980). These interactions can be between instructors, students, and other authentic characters. New technology tools, such as video conference applications or VoiceThread, which allow students to ask and respond to questions embedded in a presentation, help facilitate these types of interactions and align with sociocultural and constructivist learning theories (Piaget 1952; Vygotsky 1962, 1980). Focusing on relationships can enhance intrinsic motivations for engagement with program content (Deci and Ryan 1985). Many of the programs included opportunities for group work, requiring students to discuss and collaborate while interacting with digital tools and activities (e.g. Edstrand 2016; Delacruz 2019). In one study, students used an online carbon calculator to learn about their carbon footprints, then reflected on results in small group discussions with peers (Edstrand 2016). Interactions with peers and teachers are essential components of effective learning environments, whether students are online or in-person (Graham et al. 2019).

Principle #4- Role models. Children and youth learn from watching others around them, imitating people that they perceive are similar to themselves (Bandura 1977). Online programs can enable students to meet and learn about relevant, up-to-date science ideas from experts from a variety of fields that they may not meet otherwise. Many programs featured diverse expert guides or scientists who conveyed their knowledge and modeled behaviors (Chen and Cowie 2014; Adedokun et al. 2015). The Science Learning Hub features videos of scientists in New Zealand discussing their lives and work (Chen and Cowie 2014). Students aged 6-17 appreciated learning about relevant science topics from experts, and also expressed interest in science and science careers after watching these videos (Chen and Cowie 2014). Role models were often introduced through videos but were also sometimes portrayed as characters in virtual environments (e.g. Fokides and Chachlaki 2020). Prior research also suggests that role models such as parents, teachers and environmental educators can foster environmentally responsible behavior (Brandt et al. 2021; Chawla and Cushing 2007; Higgs and McMillan 2006; Stern et al. 2018).

Supporting learning agency

Learner agency is the ability of individuals to originate and direct their own learning based on intrinsic interests and motivations and is associated with heightened feelings of competence and autonomy (Deci and Ryan 1985; Bandura 2006; Zimmerman and Cleary 2006). When educators support student agency, it prepares them to lead and take action on environmental issues that matter to them (Barton and Tan 2010). High levels of agency are often achieved through supporting student choice and creativity, providing means for active (rather than passive) engagement, designing appropriate challenges, and communicating with positive framing. Learners' feeling of competence can also be influenced by multi-modal delivery, accounting for different learning styles or preferences (Mayer 2005; Jacobson, McDuff, and Monroe 2015).

Principle #5- Autonomy, defined as the freedom to make choices and self-direct, increases intrinsic motivation in learning environments (Patall, Cooper, and Robinson 2008; Ryan and Deci 2000). In our review, low autonomy activities, in which participants had no choices or were only passive recipients of information, were associated with less positive outcomes than activities with moderate and higher levels of autonomy. Moderate levels of autonomy enabled some independence, but choices were constrained or limited. For example, students might be following a singular path with choices to click or not click on static information, or answering a question posed by an educator using specific tools and actions. In programs designed to support high levels of autonomy, students had freedom to "move around" in virtual space and direct their own learning. Elementary school students in Taiwan enjoyed exploring a virtual ecological pond; they were excited that they could move around independently to explore above or under the surface of the water to see and learn about aquatic insects, fish and plants (Tarng et al. 2010). Some programs required students to create learning artifacts, either as a final product at the end of the experience, or as part of a contest. High levels of autonomy are also evident when students can share their understandings and thoughts on a topic in their own way, without a prescribed procedure. Ultimately, a combination of structured support (guidance) and autonomy can be beneficial when learning challenging new skills and ideas. For example, educators can provide structured support by teaching specific knowledge and skills that will be useful and then challenging students to make choices and follow their interests in enacting solutions (Rimm-Kaufman et al. 2021).

Principle #6- Active involvement. Constructivist theorists suggest that students appreciate and benefit from playing active roles in their own learning rather than being passive recipients of knowledge (Dewey 1938; Freire 1970). There are many ways this can occur in online learning environments. Students can do an activity in the midst of a program, such as an observational or nature journaling task, or data collection, analysis or interpretation. Active involvement was often seen in challenge or problem-based programs (e.g. Zydney and Grincewicz 2011), simulations, self-guided virtual tours where they can zoom around, pause, and read to learn more (e.g. Tarng et al. 2010; Mead et al. 2019), and when students had their own computers or mobile devices to actively participate rather than just passively watching a single screen. In some cases, students also designed products (Barak and Ziv 2013; Hartley et al. 2018). In one program, high school students used a web-based platform to create learning activities that were uploaded and utilized by others who visited a particular place (Barak and Ziv 2013).

Principle #7- Challenge. Cognitively challenging tasks require students to stretch beyond what they already know and apply knowledge to new concepts and situations, engaging in tasks such as creating products or solutions to complex problems. Magana's T3 Framework for Innovation (2017) posits three hierarchical domains of technology that require increasing levels of cognitive engagement. Translational use is the lowest level, and most prevalent in schools: students are simply accessing and acquiring surface-level knowledge. In the transformational domain, students participate in tasks such as producing digital representations of concepts and designing or creating digital tutorials to teach others what they know. The transcendent domain stretches students to create their own lines of inquiry and design solutions for problems that matter to them. The T3 framework roughly mirrors Bloom's Taxonomy, which is also hierarchical, and categorizes reasoning skills into six levels: remembering, understanding, applying, analyzing, evaluating and creating (Anderson et al. 2001; Bloom et al. 1956).

Although many programs described were translational or focused on remembering or understanding, a few involved students in active problem solving required higher levels of cognitive engagement (Barbailos et al. 2013; Grotzer et al. 2013; Zydney and Grincewicz 2011). For example, a simulation called Pollution Solution exemplifies higher levels of cognitive engagement. Students took on the role of interns at an environmental consulting firm, considering a case from a company that was sued on behalf of the Environmental Protection Agency for violating the Clean Air Act (Zydney and Grincewicz 2011). They watched videos of experts discussing potential solutions, asked questions, and analyzed different perspectives to devise a unique solution to bring the energy plant into compliance. Student participants were able to integrate diverse perspectives into their thinking about the problem.

Principle #8- Use of multiple modalities. Technological tools allow educators to easily use multiple modalities. Words (written or spoken), visual representations (e.g. videos, pictures, maps, graphs) and actions (kinesthetic tasks that involve physical activity) can be integrated into learning experiences. These different modalities can be combined to allow students to engage with the content in more than one way. One study compared the use of different modalities in aiding elementary students' understanding about health and environmental impacts of bottled water (Salmerón, Sampietro, and Delgado 2020). The researchers found that videos explaining a topic from an expert's perspective were more useful than text in increasing awareness. However, students who read text included more details in their written responses than students who only watched videos. This research confirmed that that each modality can serve a different purpose. Hearing a voice (and/or seeing a person explain a topic) may be more persuasive in shifting awareness about a controversial topic than text alone, yet text can aid in developing deeper knowledge integration.

The cognitive theory of multimedia learning provides useful guidance about optimizing cognitive processing through instructional design (Mayer 2005) (see Table 1). According to research aligned with this theory, each modality or combination of modes serves a purpose in helping students' process ideas and information. A few suggestions include:

- Highlighting essential material and eliminating extraneous material aids in processing (Mayer and Fiorella 2014).
- Printed text may not be needed along with spoken text, unless it is embedded within a graphic that is used to illustrate a complex concept or process (Kalyuga and Sweller 2014).
- Asking students to explain ideas in their own words (orally or in writing) or with models improves processing and can cement learning (Mayer 2014).

Principle #9- Positive framing. Emphasizing the potential for positive solutions or outcomes and drawing attention to what can, has or might be done can enhance feelings of hope and agency rather than despair (Bandura 2006). Positive framing was illustrated in descriptions of successful efforts to protect species and in modeling or descriptions of pro-environmental actions. One study found that a video that narrated a success story about the recovery of Oregon Chub in a local river influenced high school students' knowledge and attitudes toward the Endangered Species Act (Kleinhenz and Parker 2017). Authors felt that having multiple narrators share stories about collective actions that resulted in positive outcomes for the species shifted students views about protection of Endangered Species (Kleinhenz and Parker 2017).

Completing the experiential learning cycle

Completing the experiential learning cycle involves surrounding a direct experience with intentional preparation and reflection on that experience (Kolb 2015). It can also be enhanced through real time feedback to enrich the experience itself. This feedback can serve multiple functions, including keeping learners on track with specific learning objectives, giving instructions or technical support, providing encouragement, linking content to prior knowledge, and ensuring a holistic and connected experience that links parts of the learning cycle (from preparation through reflection and subsequent application of new knowledge).

Principle #10- Preparation. Each online program depended on foundational skills and knowledge in addition to the technical skills necessary to navigate the experience. Preparing students with the required knowledge and skills prior to, or at the beginning of a program allows them to focus on new concepts and use the technology successfully. An educator in Ecuador who worked with kindergarten students prepared students to design their own virtual field trips for another class by brainstorming ideas for the project using Padlet and showing her students an example of a virtual field trip to help them see possibilities for their final product (Delacruz 2019). Learners need instructional guidance as they explore multimedia environments, to help them know what to pay attention to and how to interpret what they are seeing (Cook 2006). As the number of technological tools grows, students will need to be directed toward important features and how they work so that they can proceed with the task or activities (e.g. Barak and Ziv 2013; Cohn et al. 2014; Delacruz 2019).

Principle #11- Feedback. Feedback, whether technical, or from peers or an instructor, plays an important role in enhancing learning and performance (Lowenthal et al. 2020; Wisniewski, Zierer, and Hattie 2020). Technical feedback is embedded within the design of a virtual environment or program. For example, one program utilized emoticons, music and visual effects (e.g. brightening or darkening a scene to highlight the impacts of virtual actions) to guide students in their decision making (Barbailos et al. 2013). Explanatory feedback, which "provides the learner with a principle-based explanation about why an answer was correct or incorrect" is more helpful for novice learners (Johnson and Priest 2014, 449). This type of feedback was provided by a scientist in a study by Fauville (2017); students asked questions after hearing an online lecture, and the scientist responded individually to students, extending their learning. Question and answer formats are one of many ways to provide feedback in online contexts. It is noteworthy that the majority of feedback examples highlighted in the programs we reviewed was technical; only two programs mentioned the use of peer or instructor feedback.

Principle #12- Reflection. The practice of reflection provides explicit opportunities for learners to integrate concepts and process new experiences can lead to better learning outcomes (Celio, Durlak, and Dymnicki 2011). In one study, open-ended reflection questions were embedded within a simulation (Zydney and Grincewicz 2011). For example, students were asked: "After hearing the different expert perspectives, how have your ideas about the problem changed?" The inclusion of reflection as part of a holistic learning experience can enhance learners' abilities to draw conclusions and apply their learning in a new context, thus enhancing environmental literacy outcomes (Lee, Stern, and Powell 2020; Kolb 2015; Stern and Powell 2020).

Exemplars of programs that utilized multiple principles

To better illustrate the principles defined above, we examine three programs in more detail. For these three examples, we chose programs that had uniformly positive outcomes, measured more than just knowledge, and served a variety of ages and audiences.

Web-based field trips

One study focused on a series of electronic field trips called "zipTrips" for middle school students ($n = 967$) (Adedokun et al. 2015**)**. A zipTrip is a web-based field trip comprised of videos, lesson plans and 45-minute synchronous programs. Through this program, students are introduced to a diverse group of scientist *role models* who model scientific *inquiry*, discuss their career pathways and explain the societal *relevance* of their work. Students *interacted* with the scientists by sending in questions, which were addressed at the end of the program and in follow-up posts after the program. This program was iteratively developed with feedback from students and educators, and scaled up to reach thousands of students over many years. Sixth through eighth grade students showed significant, positive changes in perceptions of scientists after participating in the program.

An educational video competition

Contests can be an effective way to actively involve students in *challenging, autonomous* tasks (Hartley et al. 2018). European students aged 7-18 ($n = 341$) were asked to prepare a two-minute video on the *social-ecological* issue of marine litter, addressing several questions. Why is marine litter a concern? What can be done? What has been done in our school/local community to address it? Students were *actively engaged* in research and film design. Several of these questions challenged students to find solutions for marine litter. Participating students made pre-post-test gains in knowledge, awareness, and reported changes in attitudes and behaviors (Hartley et al. 2018).

A place-based digital earth program

The Crow Country Digital Globe was designed by a group of tribal representatives, educators and scientists who wanted to address underrepresentation of American Indian students and teachers in geoscience and utilize technology to help students understand land management issues on the Crow Reservation (Cohn et al. 2014). This *place-based* program for upper elementary students ($n = 55$) focused on land use and changes over time in their community. The authors highlighted the importance of using "local, visual examples in culturally relevant contexts to convey the complexity of interconnection among the atmosphere, hydrosphere and biosphere as well as their relationship to people and place" (Cohn et al. 2014, 215). *Multiple modalities* were used to present concepts, including aerial photographs of historic images and interactive Google Earth technology to draw students' attention to changes in the physical and cultural landscape over time and make *social-ecological connections*. Students had *autonomy* and were *actively involved* when they used Google Earth to find answers to *challenging,* inquiry questions. Participants exhibited gains in knowledge about how rivers change over time and causes of flooding, and interest in and enjoyment for learning about earth science through Google Earth. The interdisciplinary team recommended how others should *prepare* students for similar programs using Google Earth or similar software. They suggested sequencing that allows participants to explore first, familiarizing themselves with some of the tools and features, and then introducing participants to data layers and how the maps and aerial photos interact to provide information prior to beginning more focused lessons on a given theme (Cohn et al. 2014).

Discussion/future directions

In this systematic literature review, we first identified peer-reviewed research (2010–2020) that investigated digital EE and STEM programs for youth grades K-12, then coded the articles to identify the programmatic characteristics described in the studies as well as the associated participant outcomes. This allowed us to explore program characteristics that were design features of programs with one or more positive outcomes so that we could identify the most promising approaches. We then synthesized these promising approaches and developed 12 guiding principles for developing online EE programs that enhance environmental literacy (see Table 5).

Because e-learning and online programming are new for many EE organizations, future research should explore a broader group of programmatic characteristics and identify gaps in the current literature. For example, emotional support behaviors, such as responsiveness, positive communication and sincerity on behalf of instructors were not tested in the reviewed literature, but a growing body of literature in the formal and informal education literature suggest their importance for enhancing positive outcomes for youth in EE programs (e.g. Allen et al. 2019; O'Hare et al. 2020). The COVID-19 pandemic has reminded educators of the importance of providing emotional support to their students, especially in online learning environments and when many students are under a lot of stress (Martin and Sorenson 2020).

Similarly, many of the theories cited in the reviewed studies (Table 1), such as self-determination theory, constructivism, and sociocultural learning theory, are likely familiar to environmental educators. However, other theories, such as the cognitive theory of multimedia learning (Mayer 2005) may be less familiar, and worthy of additional consideration when designing and researching online programs. The broad diversity of measured outcomes across the reviewed studies also suggests the relevance of additional theories – in particular, Kolb's experiential learning cycle, Bloom's taxonomy and Magana's T3 framework. The experiential learning cycle helps to situate online EE experiences within their broader learning environments, emphasizing the importance of preparation, experiences, reflection, and application of new knowledge. Completing the cycle may often require more concentrated planning with classroom teachers or others (Stern and Powell 2020), which can be facilitated through online components. Also, our review suggests that online EE programs requiring higher levels of cognitive engagement exist, but are the exception rather than the norm. Designing programs with these frameworks in mind may enhance participants' learning experiences and help them develop new skills and environmental actions.

Limitations

The results of this study represent the synthesis of a very small number of studies. In addition, we were reliant on the authors to describe the programs and their key characteristics. Therefore, we were only able to identify what was described. As such, we cannot claim causality in any of the patterns we observed. However, we believe the coincidence of program characteristics with positive outcomes, when aligned with sound reasoning, prior studies, and theoretical justification enables the extrapolation of reasonable principles to guide future program design and research.

Implications

The results from this review highlight the potential for digital tools to enhance environmental literacy. We do not suggest that digital learning should replace field experiences, however. Rather, each can complement the other. Children and youth undoubtedly need opportunities to witness firsthand the complexity of dynamic ecosystems and fall in love with the places and organisms around them (Baxter and Pelletier 2019; Chawla et al. 2014; Dale et al. 2020; McCurdy et al. 2010; Merritt and Bowers 2020). We suggest that online EE activities can augment real-world field experiences, particularly in consideration of the experiential learning cycle. If we combine our knowledge of EE digital learning with what we know about field-based programs, this collective work has the potential to improve environmental literacy in deeper and more lasting ways. Program providers can use their newly developed online skills to better prepare students for field trips and to conduct meaningful follow-up reflection afterward, each of which has been demonstrated to enhance learning outcomes (Lee, Stern, and Powell 2020; Stern and Powell 2020). Online programming, assuming the technological means can be made available, can also help to reach more diverse audiences otherwise separated by distance, socioeconomic, or cultural barriers. Virtual field trips can connect students to new places or enhance connection and understanding of familiar places, which may lead students to a visit or desire to protect these places (Barak and Ziv 2013; Bruch, Braun, and Teel 2011; Cohn et al. 2014; Tutwiler, Lin, and Chang 2013).

During a time of rapid innovation and advancing technologies, more research is needed to build on the preliminary trends identified in this literature review. We hope that this literature review provides a reasonable starting point for future studies and sound guidelines for practitioners who are designing online programs.

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