Received: 12 February 2019 | Revised: 2 March 2019 | Accepted: 4 March 2019
DOI: 10.1002/hbe2.141

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SPECIAL ISSUE ARTICLE
USES OF EMERGING TECHNOLOGIES

Emerging technologies as pedagogical tools for teaching and learning science: A literature review

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Abstract

This paper reviews the literature on emergent technologies from the field of science education. In an effort to summarize the current state of research, and identify specific types of technologies that have recently "emerged" in K-12 science classrooms, we review papers featured in leading science education venues in recent years. The reported trends suggest that, as a field, science education has become increasingly characterized by hermeneutic and alterity relations wherein the physical world is experienced indirectly through technological representations or has become secondary to students' experiences as it is "pushed aside" by emergent technological artifacts such as computer simulations, virtual labs, mobile devices, robots, games, and digital photography and drawing. As a result, science educators are faced with the challenge of helping students view technological instruments not as transparent and neutral devices that simply "depict reality" (naïve instrumentalism) and reveal what is "really" there (naïve realism), but as powerful epistemic tools that help co-constitute the reality being investigated, often (re)shaping what counts as "real" in revolutionary ways. It is argued that new technologies do not actually emerge in sociocultural vacuum and that more attention needs to be been given to sociocultural aspects of technological innovation in science classrooms.

KEYWORDS
academic performance, collaborative learning, students

1 | INTRODUCTION

The accelerated pace of technological innovation in recent years has created a pressing need for educational research that can help us better understand how school learning is being mediated by emerging technologies. This need is particularly strong in science, a discipline that shares a symbiotic relationship with technology (Ihde, 2009). As Bernhard (2012) writes, "all science in its production of knowledge is technologically embodied and [scientific] perception is co-determined by technology, but technology on the other hand uses the theories of science" (p. 1984). One cannot truly experience science without experiencing its technological dimension. As a result, emergent technologies have increasingly shaped students' experiences with science as well as influenced their relationships with natural/physical world. Among the technologies most commonly embedded in the school curriculum to support teaching and learning of science are electronic probes (sensors and software), dynamic modeling tools, interactive visualization tools, and integrated e-learning environments (Krajcik & Mun, 2014). Their emergent status or *newness* (Gershon, 2017) stem not only from their novel material structure (seemingly new design or look) but also from their enabling of novel ways for teachers and students to coordinate pedagogical activity, social interaction, and knowledge construction (i.e., new communicative and epistemic affordances).

Unsurprisingly, the field of science education has witnessed exponential growth in research aimed at analytically scrutinizing pedagogic use of emergent technologies. Although such a trend led to the creation of the *Journal of Science Education and Technology*, research is scattered across a wide variety of venues. In an effort to achieve more coherence and clarity, we conducted an extensive review of this literature. Our main goals were to summarize the current state of research on emergent technologies in science education, and to identify themes and gaps in this research base. Of particular interest to us was the identification of specific types of technologies (e.g., three-dimensional [3D] printers, nanotechnology, mobile phones) that have recently "emerged" in K-12 science classrooms as well as their impact on teachers and students' behaviors (ideologies, perceived affordances, attitudes, computational thinking, etc.). We were also interested in assessing science educators' theorizing and adoption of particular stances on technology (instrumentalism, technological determinism, etc.). Given the content-specific nature of our review, we deliberately avoided going beyond the field of science education. More specifically, we narrowed the scope of our review to specialized research venues central to the field (*Journal of Research in Science Teaching*, *Science Education*, *International Journal of Science Education*, *Journal of Science Education and Technology*, and *Research in Science Education*) and excluded more interdisciplinary, content-general forums (e.g., Computers & Education). In an effort to include only the most recent research, we selected 2008 as our cutoff point for year of publication. Additionally, we focused on K-12 formal education settings and excluded papers focused on teacher preparation issues.

2 | EMERGING TECHNOLOGIES DEFINED

Far from obvious, technology is a nuanced term whose meaning can vary considerably depending on one's field of scholarship, philosophical commitments, and theoretical affiliations. Often used interchangeably with terms like *technological devices*, *technological artifacts*, *technological tools*, *mediating objects*, *interactive systems*, and *technological design* (Brown & Sammut, 2012; Psotka, 2012), technology sometimes denotes engineering process whereby new devices are created and at other times its products (the devices themselves). It is also used in reference to academic disciplines or fields of study like instructional technology (Elen & Clarebout, 2012). Further, those interested in the latest technological advancements also resort to qualifiers like "emerging," metaphorically conceiving of "newness" as outward motion (Cook, 2004; Gershon, 2017). New technologies are said to naturally emerge out of or arise from previous human achievements, though what constitutes newness remains a bit obscure. As a result, academic exchanges about technology often suffer from a lack of clarity.

Given the above state of affairs, it will be convenient to begin by clarifying how science educators conceive of technology. Much of the science education literature on emerging technologies is strongly influenced by national educational policies. Particularly influential are the *Next Generation Science Standards* (NGSS), which defines the term technology "broadly as all types of human-made systems and processes… that result when engineers apply their understanding of the natural world and of human behavior to satisfy human needs and wants" (NRC, 2012, pp. 11–12). Moreover, NGSS conceives of the emergence of new technologies in terms of a relationship of interdependence among Science, Engineering, and Technology, a core idea that students must grasp as a result of their schooling experiences (NGSS Lead States, 2013). Scientific inquiry, engineering design, and technological development are part of an epistemic cycle of advancement, one continuously informing the other:

> Advances in science offer new understandings that can be applied through engineering to produce advances in technology. Advances in technology, in turn, provides scientists with new capabilities to probe the natural world at larger or smaller scales; to record, manage, and analyze data; and to model ever more complex systems with greater precision. (NRC, 2012, p. 203)

The vision projected by NGSS is that technological advancement is essentially the development of new "probes" by engineers through science-informed design. New technologies are portrayed as knowledge-making tools designed for the specific purpose of improving scientists' investigative work and facilitating new scientific discoveries. The "newness" of new technology is constructed strictly on epistemic grounds, that is, in terms of its capability to enable new scientific knowledge.

Such a vision is consistent with what some philosophers of technology have described as the rise of *technoscience* (Ihde, 1991)—a trajectory of knowledge advancement whereby technology has become an increasingly integral part of science. As Ihde (2009) writes, "all modern science is instrumentally or technologically embodied… no instruments, no science" (p. 35). Moreover, emerging technologies create new empirical/theoretical affordances (Gibson, 1979; Heft, 2003) or opportunities for action (e.g., possibility of improved observation, measurement, modeling) which scientists can capitalize upon and hence transform potential into actual discovery.

Consistent with the technoscience argument, the world of science has recently witnessed the advent of what has come to be known as *the fourth science paradigm* (Hey, Tansley, & Tolle, 2009), that is, scientific discovery based on massive datasets and intensive computing. Unlike "small data" science, data-intensive science relies on large-scale networks of densely deployed sensors capable of real-time, remote monitoring of complex environmental systems. Enormous quantities of data flowing in real-time from distributed locations are stored as massive databases that can be accessed online by scientists, students, and citizens. With science moving toward being more computational and database-centric, calls have been made for science education to follow suit. This is particularly evident in the NGSS, which includes "computational thinking" as one of several essential practices of science that K-12 students should master. However, no explicit definition is given, and the very limited information provided suggests algorithmic problem solving. Such a lack of information is problematic given the philosophical difficulties of defining the "computational paradigm" (Denning, 2010).

While the close interrelation of science and technology is undeniable, the impact of emerging technologies is in fact much broader and can be felt throughout society, beyond scientific circles. In addition to enabling scientific advancement, new technologies also have a deep impact on everyday human experience. Because modern technology also mediates much of our everyday experiences with the world, they give rise to novel human-world relationships, often drastically reshaping how we generally relate to the world and experience reality (Verbeek, 2001). Evidence abounds that emerging technologies give rise not only to new ways of seeing and understanding the natural world but also to new ways of being-in-the-world (new personal identities, ways of socially relating to others, etc.). Identified by NGSS as a second core idea, namely "the influence of engineering, technology and science on society and the natural world" (NRC, 2012, p. 210), the social and personal affordances of emerging technologies for everyday users have been well documented (Cook, 2004; Crystal, 2011; Kolko, Nakamura, & Rodman, 2000; Olson & Olson, 2003; Richardson, 2001). This literature emphasizes the experiential dimension of technological advancement as well as its personally relevant and socially transformative nature.

3 | SEVEN EMERGENT TECHNOLOGIES USED IN SCIENCE EDUCATION

We now turn our attention to the main emergent technologies used for teaching and learning science, as revealed by our literature review. More specifically, attention is given to (a) computational thinking; (b) simulations, dynamic visualizations, and virtual labs; (c) computational modeling; (d) mobile devices; (e) pedagogic robotics; (f) gaming and technology-mediated play; and (g) creative and artistic technologies.

3.1 | Computational thinking

Overall, research about computational thinking in science education is scarce. Our search revealed only three papers (one theoretical and two empirical) on the topic, all published in the *Journal of Science Education and Technology*. These papers are summarized below.

Drawing on the existing computational thinking literature and interviews with mathematicians and scientists, Weintrop et al. (2016) propose a definition of computational thinking in the form of a taxonomy consisting of four main categories: (a) *data practices* (collecting, creating, manipulating, analyzing, and visualizing data); (b) *modeling and simulation practices* (using computational models to understand a concept, find and test solutions, assessing, designing, and constructing computational models); (c) *problem solving practices* (preparing problems for computational solutions, programming, choosing effective computational tools, assessing different approaches/solutions to a problem, developing modular computational solutions, creating computational abstractions, troubleshooting, and debugging); and (d) *systems thinking practices* (investigating a complex system as a whole, understanding the relationships within a system, thinking in levels, communicating information about a system, and defining systems and managing complexity). Moreover, several examples are provided to illustrate these practices, including a lesson wherein students investigate the laws of physics that govern video games. However, no evidence is provided of the effectiveness of approaching integration of computational thinking into science education in the manner described; the authors only articulate and illustrate a theoretically informed position.

Using the term computational thinking to describe the ability to think with the computer as a tool, Berland and Wilensky (2015) describe a study in four urban middle school classrooms comparing the effectiveness of curricular units in supporting students' complex systems and computational thinking. One unit used a physical robotics participatory simulation and the other unit used a virtual robotics participatory simulation. The findings of this study indicate that while both units improved student outcomes to roughly the same extent, they engendered different perspectives on the content. Students using the physical system were more likely to interpret situations from a bottom-up ("agent") perspective, and students using the virtual system were more likely to employ a top-down ("aggregate") perspective. Outcomes from this study suggest that the medium of students' interactions with systems can lead to differences in their learning from and about those systems.

Leonard et al. (2016) examined the potential of using robotics and game design to engage youth in computational thinking. This paper describes how the use of LEGO EV3 robotics and Scalable Game Design software influenced rural and indigenous students. The results of the study revealed student attitudes toward and interest in STEM careers did not change significantly. Students were able to infuse some elements of culture and place into game design. Students' self-efficacy scores on the construct of computer use declined significantly, while the constructs of video gaming and computer gaming remained unchanged. Self-efficacy on video gaming increased significantly in the combined robotics/gaming environment compared with the gaming-only context.

In sum, despite recognition both in policy and research outlets of the potential of informational technologies (computers, gaming, robotics) to pedagogically support student development of computational thinking in science, work in this area is still in its infancy. Not only does it constitute a rather esoteric notion for many science educators with limited familiarity with the computational paradigm, but classroom enactment also remains nebulous. A more solid philosophical understanding of this new scientific paradigm is clearly needed. For instance, computer scientists posit that computational thinking goes far beyond computer programming, and does not necessarily involve use of computers at all. In her seminal position paper, Wing (2006) defines computational thinking as a way of "using heuristic reasoning to solve to discover a solution" (Wing, 2006, p. 34). This could involve coding an algorithm, but it really is about embracing the way a computer interacts with information and adopting the methods used by computer scientists (e.g., working iteratively). Wing's argument is that computer science as a discipline demonstrates skills and ways of thinking that can benefit how humans use information that they collect to solve problems. It can involve using the computational power of a computer, but it does not have to.

Although only three papers explicitly mentioned computational thinking, a large number of articles examined technology-mediated classroom practices that fit with definition put forward by Weintrop et al. (2016), especially the two categories of modeling and simulation practices, and systems thinking practices. These articles are reviewed in the next sections.

3.2 | Simulations, dynamic visualizations, and virtual labs

Simulations have been the most widely researched type of computational technology in K-12 science classrooms. A large number of recent studies have examined the effectiveness of tools designed to simulate science labs, field trips, and scientific phenomena with relatively high fidelity (Table 1). The simulations featured in these studies varied in terms of functionalities (i.e., simulation of a phenomenon, virtual lab), disciplines (chemistry, biology, life sciences), and purpose

TABLE 1 Studies about simulations, dynamic visualizations, and virtual labs

Reference	Type of technology
F. R. Sullivan (2008)	Lego Mindstorms construction kits (features the RCX programmable brick, sensors, motors, and building piece) and Robolab software
Voyles, Fossum, and Haller (2008)	RoboLab: Lego robot kit
Y. S. Hsu (2008)	SeasonSim (computer simulation) is used as part of an online lesson on seasonal changes in high school
Jaakkola, Nurmi, & Veermans, (2011)	Simulation of electricity ("electricity exploration tool EET")
Scalise et al. (2011)	Science simulations and virtual labs (literature synthesis)
Plass et al. (2012)	Computer simulations for chemistry learning
Quellmalz et al. (2012)	SimScientists program (simulation-based, curriculum embedded assessment program) LMS
Adedokun et al. (2012)	Uses virtual field trips (zipTrips) with middle school students
Ryoo and Linn (2014)	Interactive dynamic visualizations from WISE on photosynthesis (energy [light to chemical] transformation at the molecular level)
Tutwiler, Lin, and Chang (2013)	Use of virtual field trip—three-dimensional virtual reality learning environments for field trip (3DVLE [ft]) system
Sadler, Romine, Stuart, and Merle-Johnson (2013)	Video games (Mission biotech MBt—virtual lab) to help student use biotechnology to solve a societal problem
Kukkonen, Kärkkäinen, Dillon, and Keinonen (2014)	Simulation-based inquiry used to learn about the greenhouse effect
Zhang, Hsu, Wang, and Ho (2015)	SeasonSim is used to engage junior high students in online inquiry learning
Childers and Jones (2015)	Use a virtual and remote electronic microscope (Remote Microscopy Lab) in high-school biology
Israel, Wang, and Marino (2015)	Three games: Cell Command, Crazy Plant Shop, You Make Me Sick!
Kamarainen, Metcalf, Grotzer, and Dede (2015)	Uses EcoMUVE—Multiuse virtual environment (MUVE) – To model ecosystems (Pond and Forest)
Jagodziński and Wolski (2015)	Virtual chemistry laboratory—Simulation software with natural user interfaces
Hmelo-Silver, Liu, Gray, and Jordan (2015)	NetLogo simulation in small groups; and RepTools (a function-oriented hypermedia system presenting Struct, Behav, Functional levels of aquariums)
Chao, Chiu, DeJaegher, and Pan (2016).	Use of a sensor-augmented virtual lab with physical controls to teach gas laws to high school chemistry students
Ryoo and Bedell (2017)	Interactive dynamic and static visualizations (to support EL and non-EL's understanding of energy and matter transformation in life science)
Chao et al. (2017)	Energy3D (A simulated environment for engineering design, SEED): An environment for designing, analyzing, and constructing green buildings utilizing renewable energy
Fauville (2017)	Use a virtual laboratory and a virtual lecture to help high-school students develop ocean literacy
Al-Balushi, Al-Musawi, Ambusaidi, and Al-Hajri (2017)	Use of chemistry animations and simulations with mobile devices
S. Sullivan, Gnesdilow, Puntambekar, and Kim (2017)	Use of virtual experimentation (virtual labs) to teach mechanics concepts like pulley systems
Scalise and Clarke-Midura (2018)	3D immersive virtual environment. The New Frog VPA (virtual performance assessment) to assess middle school science inquiry skills in situ
Chen, Wang, Grotzer, and Dede (2018)	3D thinking graph (3dTG) to combine a single image/information to hypo/reasoning process using causal mapping

for integration (i.e., assessment, teaching, or both). In terms of the research population, these articles examined science learning of middle- and high-school students.

Out of the 14 articles published at *Journal of Research in Science Teaching* (top journal in the field), 2 studies used video games (Israel et al., 2015; Sadler et al., 2013), 10 integrated simulations (Bell & Trundle, 2008; Chao et al., 2017; Chen et al., 2018; Gerard, Spitulnik, & Linn, 2010; Hmelo-Silver et al., 2015; Jaakkola et al., 2011; Mulder, Bollen, de Jong, & Lazonder, 2016; Plass et al., 2012; Quellmalz, Timms, Silberglitt, & Buckley, 2012; Scalise & Clarke-Midura, 2018), and 2 used interactive dynamic visualizations (Ryoo & Bedell, 2017; Ryoo & Linn, 2014). The video games targeted topics such as cell anatomy and functions, genes and inheritance (Israel et al., 2015), and one was in the form of a virtual biotechnology lab (Sadler et al., 2013). Moreover, simulations included tools such as PlateTechtonics interactive simulation model of convection currents and plate movements (Gerard et al., 2010) and Energy3D, a simulated environment for designing, analyzing, and constructing green buildings utilizing renewable energy (Chao et al., 2017). One study (Mulder et al., 2016) employed a simulation modeling environment where students constructed glucose-insulin models using worked-out examples and saw results. Dynamic visualizations were both based on Web-based Inquiry Science Environment (WISE) (wise.berkeley.edu) on topics such as photosynthesis (Ryoo & Linn, 2014).

Different types of simulations, games, and visualizations were employed for assessment, learning and problem solving, and/or both by the authors of the studies. Two articles focused more heavily on assessment as the function of their simulations (Quellmalz et al., 2012; Scalise & Clarke-Midura, 2018). Quellmalz et al. (2012) implemented SimScientist system in curriculum for embedded formative assessment, feedback, and coaching, while Scalise and Clarke-Midura (2018) used a 3D immersive virtual environment (New Frog Virtual Performance Assessment) to assess middle-school students' science inquiry skills in situ. The remaining 10 studies employed their multimedia tools for enhancing student learning of science topics. These tools targeted improving different skills, such as inquiry (e.g., Chen et al., 2018), hypothesis generation and reasoning, and conceptual understanding (e.g., functions and behaviors of aquariums, Hmelo-Silver et al., 2015).

The effectiveness of the tools used in these studies was measured by different metrics, and an overall benefit was observed for conditions where these tools were employed. For instance, Mulder et al. (2016) observed improved learning outcomes, model quality, and model testing activities as a result of working with partial glucose-insulin worked-out models. Chen et al. (2018) also reported improved posttest scores and learning gains for students who used their 3D Thinking Graph simulation tool.

We also found several literature reviews related to the use of simulations and virtual labs. Scalise et al. (2011) published a synthesis of 79 studies integrating science simulations (73) and virtual labs (24). This synthesis reported that 53% of the studies they found observed learning gains as a result of use of simulations, 18% gains only under the right conditions, and 4% reporting no gains. Likewise, based on an extensive review of literature in the past two decades, Cheng and Tsai (2013) identify the many benefits of augmented reality technologies (both image- and location-based) for science learning. This review underscores how augmented reality technologies constitute an effective means to engage students in inquiry-based science learning and support improved spatial ability, practical skills, and conceptual understanding. Brinson (2017) reviewed recent literature related to student learning outcome achievement in nontraditional (virtual and remote) versus traditional (hands-on) science labs. All of these reviews consistently point to the overwhelming positive effect of integration of simulation technologies.

3.3 | Computational modeling

Another theme in the science education literature was pedagogical use of computational modeling—multimedia tools that provided learners with interactive visual representations of dynamic theoretical entities and complex scientific processes difficult to represent in a science textbook (Ardac & Akaygun, 2004). Computational modeling allows students to visualize science content while developing domain specific, authentic reasoning skills, thereby supporting deep conceptual understanding (Wilkerson-Jerde, Gravel, & Macrander, 2015). Several studies investigated computational modeling in K-12 classroom settings (Table 2). Interestingly, learning complex systems was a common focus of these studies, many of which reported that students encountered difficulties interpreting and understanding complex systems that represented a class of phenomena across varied domains such as chemical reactions, ecosystems, and traffic jams.

Several of the above studies focused on agent-based computational models (ABMs)—systems that explicitly captured agents and their interactions by representing individual actors as computational objects with assigned rules. ABMs have been shown to be effective pedagogical tools in learning about emergent phenomena in multiple domains. Rates et al. (2016) studied the effectiveness of using an agent-based model in improving high school students' understandings of complex systems components (e.g., the Chesapeake Bay watershed). This study found that students showed more expert thinking about the complex system of the Chesapeake Bay watershed. Similarly, Pallant and Lee (2015) investigated how students constructed scientific argumentation with evidence from computational models of climate change. After experimenting with dynamic climate models and observing changes in the ABM, students were able to use evidence from the associated graph outputs to develop their scientific arguments. Brady et al. (2015) resorted to a class of learning environments called Emergent Systems Sandboxes (ESSs)—a specified form of virtual construction environment that allows users to create, explore, and share computational models of emergent dynamic systems. ESSs were shown to effectively support iterative and social learning, enabling learners produced, shared, and reviewed each other's computational artifacts. Pierson and Clark (2018) investigated the role of external audience in engaging students in computational modeling. This study found

TABLE 2 Studies about computational modeling

Reference	Type of technology
Chang, Quintana, and Krajcik (2010)	Handheld palm computers and Chemation (flipbook-style animation) used to model chemical phenomena
Dickes and Sengupta (2013)	Agent-based modeling: Birds & Butterflies Random Phenotype Model using NetLogo
Berland and Wilensky (2015)	Virtual and physical robotics with networked participatory simulation tool (VBOT)
Basu, Sengupta, and Biswas (2015)	Multi-agent-based computational models (MABMs)
Brady, Holbert, Soylu, Novak, and Wilensky (2015)	A class of constructionist learning environments, called emergent systems sandboxes (ESSs)
Wilkerson-Jerde, Wagh, and Wilensky (2015)	Modelling of population ecology with Deltatick (a visual block-based interface)
Pallant and Lee (2015)	Computational climate models with visualization
Lamb (2016)	2D online simulation and 3G game modeling of viral outbreak around the world
Leonard et al. (2016)	LEGO EV3 robotics with scalable game design software
Rates, Mulvey, and Feldon (2016)	Agent-based simulations and models of complex systems: a participatory, collaborative computer game
Kern and Crippen (2017)	Modeling the impact of anthropogenic climate change on ecosystem with an interactive cyberlearning system
Pierson and Clark (2018)	StarLogo Nova-visual programming environment for agent-based models (ABMs)

that students who designed for an external audience of younger children displayed greater conceptual growth about mechanisms that cause tidal bulges.

Several studies also identified forms of scaffolding that effectively supported learning through agent-based computational modeling (Brady et al., 2015; Dickes & Sengupta, 2013; Pierson & Clark, 2018; Schwarz et al., 2009), online mentoring from scientists (Scogin & Stuessy, 2015), and app-based procedural guidance (Falloon, 2017). For instance, modeling environments like StarLogo Nova (Pierson & Clark, 2018) and Netlogo (Dickes & Sengupta, 2013) were shown to reduce the syntactic tension experienced by students by allowing them to program through graphical "blocks" rather than text-based commands. Pallant and Lee (2015) described how students needed explicit scaffolding to recognize and properly respond to model limitations and uncertainty. In addition, Basu et al. (2015) described how teachers provided appropriate scaffolds to help students to correct relations in their ecosystem model.

3.4 | Mobile devices

Mobile learning is yet to enter mainstream research in science education. Our efforts revealed only four publications (one literature review and three empirical studies) in recent years, all published in the *Journal of Science Education and Technology*. Crompton, Burke, Gregory, and Gräbe (2016) conducted an extensive review the literature on mobile learning of science between the years 2000 and 2015. It was reported that a variety of research methods were deployed, that the majority of the studies were conducted in the area of life sciences in informal elementary settings, and that mobile devices enabled students to more easily make real-world connections. Moreover, mobile devices were typically used by students to consume knowledge. Few science educators took advantage of mobile devices' potential to enable students to become producers, collaborators, and creators of knowledge (Crompton et al., 2016).

The three empirical studies focused on variety of mobile technologies, topics, and grade levels. Hochberg, Kuhn, and Müller (2018) developed science activities wherein physics students used *smartphones*' built-in sensors to investigate pendulum mechanics (acceleration, etc.). Smartphones served as experimental tools, affording students the ability to make measurement and perform scientific investigation. McMahon, Wright, Cihak, Moore, and Lamb (2016) used a digitized podcast software to deliver read-aloud testing accommodations (audio version of test questions playable on *iPod touch*) to middle-school students with disabilities and reading difficulties. Falloon (2017) used *iPads* with a series of science apps to scaffold elementary students' practical work during the hands-on science activities. The app-based scaffolds helped students structure their experiments, understand procedures, think about variables, and communicate outcomes. Focused on the impact of using mobile devices on student achievement, the most commonly measured outcomes across these studies were students' basic scientific knowledge or conceptual understanding as well as students' attitudes, motivation, and engagement.

3.5 | Pedagogic robotics

Two studies used robots in teaching inquiry skills to middle- and high-school students (F. R. Sullivan, 2008; Voyles et al., 2008). F. R. Sullivan (2008) examined students' open-ended inquiry in learning basic computer science concepts (e.g., flow, iteration, parallel processing) by using Lego Mindstorms construction kits and Robolab software. Lego Mindstorms includes RCX programmable brick, sensors, motors, and building pieces. They found positive effects where students' systems' understanding improved as a result of engaging with the robots. Voyles et al. (2008) used Lego Engineering robots and the accompanying platform (Robolab visual programming language) investigating gender bias in teaching robotics, and the difference of boys and girls in terms of their interest, prior knowledge, and perceptions of learning with Lego robots. In this study, students built, designed features for, and programmed Lego robots. No gender difference was found in achievement and interest.

3.6 | Gaming and technology-mediated play

Our reveal also indicated that growing numbers of science educators have utilized educational computer games. Among the most popular types of games used by science educators are simulations. C.-Y. Hsu, Chin-Chung Tsai, and Liang (2011) used a computer game that simulated shadow formation in daylight to teach a group of preschoolers. Anderson and Barnett (2013) had middle-school students play the 3D computer game *Supercharged!*, which simulated electrostatic phenomena such as how charged particles interacted with electric and magnetic fields. Price et al. (2016) used *Code Fred: Survival Mode*, an online educational game that simulated human body systems. Considerably less common in science education is the use of educational games that do more than merely simulate natural processes. Also relatively uncommon is the use of video games for learning science at the elementary school level. This is sharp contrast to middle- and high-school where science educators have more commonly favored the use of video games as a means to engage students in inquiry-based science learning. To do so, these educators have typically resorted to "computer-based narrative discovery learning games" in an online collaborative environment accessible to K-12 students.

In addition to the above empirical studies, we also found theoretical papers that provided an overview of the literature on games in science education (Barko & Sadler, 2013; Li & Tsai, 2013). The papers consistently emphasize that electronic games have an unquestionable pedagogical value as tools for effectively engaging students in science learning. Such value stems from gaming activity's capability to promote playful thinking in science learners. However, as emphasized by advocates of "learning through play and playful exploration", a distinction must be made between laissez-faire *play* (purposeless and entertainment-focused) and *structured* or *guided play* (purposeful and learning-focused) (Miller & Almon, 2009). Serious gaming, as conceived in the current scholarly literature, is more consistent with the latter (i.e., an engaging yet informational activity with a clear conceptual focus and sett of learning objectives).

A noticeable trend within this literature is social relevance. Several studies focused on games that involved using science to help people and directly benefit society. Typically focused on socioscientific issues (scientific issues with social ramifications), these games positioned students as scientists shaping society, contributing solutions to real-world challenges, and helping to improve the health and safety. Using mobile-augmented reality technology, Chang, Hsu, Wu, and Tsai (2018) engaged students in decision-making activity wherein students had to investigate whether school grounds had been polluted by an imagined nuclear radiation accident and decide how to best remediate the environmental problem. Students were provided with Android tablet computers with GPS technology and to collect virtual radiation data and conduct interviews with virtual characters. Sadler, Romine, Menon, Ferdig, and Annetta (2015) used a computer-based game with a biotechnology theme (Mission Biotech). As players, students had access to a large laboratory modeled after a biotech laboratory, being tasked with identifying the infectious agent causing a viral outbreak. Bergey, Ketelhut, Liang, Natarajan, and Karakus (2015) used *SAVE Science World: Sheep trouble* with a group of middle-school students. In this immersive virtual environment, students chose an Avatar and then explored a virtual world called *Scientopolis* as they set out to help Farmer Brown whose sheep were dying. Across these studies, educators capitalized on the socioscientific affordances of gaming technologies, strategically using them to create *altruistic productive spaces* (Haun-Frank, 2011)—social spaces where students could experience science as vehicle for helping others (family, community, and larger society) and imagine themselves as scientists whose professional activities are devoted to a greater good.

3.7 | Creative and artistic technologies

Another noticeable theme in the science education literature was use of emergent technologies with creative and artistic affordances such as digital photography and technology-mediated drawing. In two studies, this took the form of *photography-based science inquiries*—discovery activities wherein students made a photographic record of their experiment and data, and participated collaborative critique of science photographs taken inside class or outdoors (Boyce, Mishra, Kristy, Halverson, & Thomas, 2014; Zimmerman & Weible, 2018). Likewise, Price, Lee, and Malateska (2014) provided children with photographs as well as stereoscopic visualizations (3D images) and then asked to reproduce them in writing. In Chang (2018) and Chang et al. (2010), a drawing technology called DrawScience was used by high-school students to create visual representations of states of matter and the carbon cycle. And, Lee (2015) had elementary students record slow-motion videos of themselves making unique body movements (e.g., a soccer kick) with high-speed cameras, use stop-motion animation software to create models of motion (series of still images) and then hand-drawn original flipbooks. Across these studies, use of emergent technologies had the effect of make the science learning process more aesthetically pleasing and visually rich. Consistent with STEAM instructional approaches (Maeda, 2013; Radziwill, Benton, & Moellers, 2015), students were afforded opportunities to use emergent technology creatively (i.e., engage in creative visual production and expression) while learning science.

4 | DISCUSSION

The above trends highlight the increasingly technological nature of science education. More than ever before, the teaching and learning of science in K-12 classrooms is being mediated by emergent technologies that shape not only how students perceive but also how they experience the natural or physical world (Verbeek, 2001). As "naked" perception (I—world) gives away to mediated perception (I—technology—world), more and more students derive their scientific understandings from technologies that mediate, augment, and simulate the natural world. Far from neutral or transparent, these technologies have an experiential impact and can give rise to new ways of relating to their world (social and physical). This possibility is raised by the philosopher of technology Ihde (2009), who distinguishes among three different types of technology-mediated relations between humans and their world ("→" is used to symbolize human action, whereas "—" denotes a conjoint relationship):

Embodiment relations: (I—technology) → world

Hermeneutic relations: I → (technology—world)

Alterity relations: I → technology (—world)

Embodiment relations involve use of technologies that enhance our perceptual abilities and sensorial input (e.g., telescopes, microscopes). The technology itself is transparent in the sense that it extends our bodily experience (like "perceptual prosthetics") without drawing attention to itself. In contrast, *hermeneutic relations* entail use of technologies that enable us to read or interpret the natural world (e.g., thermometers). The technological tool itself is not transparent as it must be read as it generates representations of the world like numbers and inscriptions (the world is "read through" the technology). Lastly, in *alterity relations*, technology itself becomes the relational other (e.g., robots, automated machines). Rather than relating to the world via technology, humans relate to technology itself as nature fades into the background of the human experience where is hardly even noticed or attended to.

From the above perspective, the reported trends in our literature review suggest that, as a field, science education has become increasingly characterized by hermeneutic and alterity relations wherein the physical world is experienced indirectly through technological representations or has become secondary to students' experiences as it is "pushed aside" by emergent technological artifacts. As such, science educators are faced with the challenge of helping students view technological instruments not as transparent and neutral devices that simply "depict reality" (naïve instrumentalism) and reveal what is "really" there (naïve realism), but as powerful epistemic tools that help co-constitute the reality being investigated, often (re)shaping what counts as "real" in revolutionary ways.

The literature reviewed above also suggests that the field of science education has focused almost exclusively on psychological aspects of emergent technologies (cognitive processes and conceptual issues). With regard to pedagogical use of technology, science educators have given primacy to conceptualization by focusing their research efforts mainly on issues related to student cognitive development such as effectively using emergent technologies to promote student acquisition of more sophisticated science understandings in science. Considerably less attention has been given to sociocultural aspects of technological innovation in science classrooms such as its impact on existing school culture or the emergence of new identities, cultural values, and interactional processes in the science classroom. For instance, evidence exists that efforts to use educational videogames and social media like Facebook are often met with resistance from science educators who consider such technologies inappropriate for classroom settings (Muehrer, Jenson, Friedberg, & Husain, 2012; Rap & Blonder, 2016). This resistance is unsurprising since "work" is a cultural value central to contemporary school practices (Ildefonso, 2011). Rooted in capitalist ideologies, such a cultural value is largely inconsistent with emerging technologies such as video games, mobile phones, and social media, all of which are typically associated with alternative social practices such as "play" and "leisure." As a result, introduction of these new technologies typically falls short of engendering any meaningful change or being a truly transformative moment, regardless of how recently they were invented. Truly understanding pedagogical use of emerging technologies requires careful consideration of not only their novel cognitive affordances but also the sociocultural context of resulting behaviors. Effective promotion of science earning seems less likely without the realization that new technologies do not actually emerge in sociocultural vacuum and that users (scientists as well as science learners) do exercise their human agency as free actors whose behavior is not simply determined (dictated) by the new technology.

In a recent call for papers in the *Journal of Research in Science Teaching*, Neumann and Waight (2019) highlight the rapid advancements in instructional technologies in the past decade, as well as the pressing need for science educators to research how "21st century cutting-edge technologies" have been/can be applied to the teaching and learning of science. Most notable among these are learning analytics, natural language processing, machine learning, adaptive feedback technologies, IoT (Internet of Things), and interactive dashboards; all technologies that rely on massive data collected about choices and actions of learners enabling the technology-rich environments to provide personalized real-time feedback. Consistent with this call, we did not find any studies using these technologies. Filling this void can certainly could prove impactful for future research in science teaching and learning.

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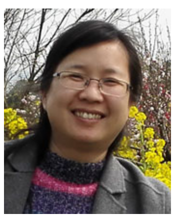

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How to cite this article: Oliveira A, Feyzi Behnagh R, Ni L, Mohsinah AA, Burgess KJ, Guo L. Emerging technologies as pedagogical tools for teaching and learning science: A literature review. *Hum Behav & Emerg Tech*. 2019;1:149–160. https://doi.org/10.1002/hbe2.141