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Educational Opportunities and Challenges in Augmented Reality: Featuring Implementations in Physics Education

JOEL WEIJIA LAI AND KANG HAO CHEONG, (Member, IEEE)
Science, Mathematics and Technology Cluster, Singapore University of Technology and Design (SUTD), Singapore 487372
Corresponding author: Kang Hao Cheong (kanghao_cheong@sutd.edu.sg)

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ABSTRACT This review paper provides the conceptualization and development of augmented reality (AR) environment for education by featuring implementations in physics education. The use of AR creates an environment designed to fully incorporate next-generation AR-aided notes, virtual laboratory and interactive problem-based learning with real-time automated generation of application-centric scenarios. This can be carried out via the fusion and technologizing of pre-existing teaching materials (such as books and notes) using AR and be mobile device friendly to fully leverage on learning beyond classrooms. Such a method is proposed to give students the access to resources anytime, anywhere without the spatial and temporal restrictions of synchronous-learning. This review discusses the advances of AR as an important tool in physics education, identify potential challenges and envisions the future by surveying recent trends and reviews. We provide perspective on practical AR implementation and evaluation for educators and school administrator, and potential academic advances through physics education research for researchers.

INDEX TERMS Augmented reality, immersive technology, education development, physics education research.

I. INTRODUCTION AND OVERVIEW

Mixed reality, as a concept, has existed since the conception of creating illusions of alternative realities, popularised by science fiction, as with many other technological advances [1]. Due to the advent of technology, mixed reality has been used for professionals in areas such as medical, flight, design, the humanities, the languages, and military training [2]–[10]. Augmented reality (AR) bridges the virtual and real worlds and is one of the common implementations of mixed reality technology. The efficacy of AR implementation in training is successful and has also been shown to meet the goal of providing professional training of student through practical training. The introduction of VR [11] in higher vocational education has made access to learning materials easier and improve interaction between materials and students, thus improving efficiency of solving and realizing a task [12], [13]. AR technology allows information, in the form of text, images, sound or objects to be superimposed in real environments so that students can participate in a variety of situational simulations or visual activities while learning. The propagation of such technologies are further accelerated by the extensive reach of mobile devices [14].

With training as its main usage, it led to the natural adoption of such technologies being used in education as well [15]. It has wide usage in physics education where very often, the physical realities cannot be easily experienced in day-to-day life. It enhances the spatial and temporal reality by augmenting it with virtual information accessible through touch, sight and hearing. The coexistence of virtual objects responding to constraints set by real environments allows for visualisation of complex phenomena or abstract concepts not usually possible in the real world [16]–[18]. The possibilities offered by this technology allow designing physics educational environments that involve non-traditional teaching and learning practices. The availability of Massive Open Online Courses (MOOC) has also facilitated the propagation of AR implementation [19], [20].

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Some examples of AR implementation in physics education include, visualizing vector fields in electromagnetism from real world objects [21], [22]; animating internal motion of the Stirling engine and flow of air in a thermal physics experiment [23], [24], and; operating complex laboratory equipment for physics experiments to build conceptual knowledge [25], [26]. These can be made visually realistic through augmenting virtual objects. The mobility provided by hand-held devices facilitate interaction between students and the learning environment. AR allows learners to gain a heightened immersive awareness of the surrounding environment. Students often find active participation in such activities more interesting, intrinsically motivating, and closer to real-world experiences than other learning modes. The introduction of hands-on practise in the real-world encourages active learning; consequently, AR is regarded as a promising tool in education that supports and helps improve students' learning motivation and interest in educational settings [27]. New possibilities for teaching and learning emerge with the advances of AR and have been widely acknowledged as beneficial by educational researchers. These educational benefits have made AR one of the key emerging technologies for physics education and motivates the discussion in this review.

As a foreword, when we mention AR, we are not simply referring to innovative technologies, such as mobile phone, wearable devices, and immersion technologies. Instead, we take a broader definition by also including AR design, implementation and integration into both formal and informal teaching and learning environments. This broadens the scope and ensures that this review remains pedagogically relevant even with evolving technologies. Thus, the purpose of this article is to broadly establish the important alignment between technology design with instructional approach and learning experiences when using AR. Furthermore, the objective is twofold: to provide school administrators and educators a framework on successful implementation and integration of AR to teaching and learning environments. For the education researcher, it also provides a collection of frontier topics for AR in physics education.

The AR pedagogical environment can be considered a next-generation evolution of the traditional teaching approaches, with modern technology being a key enabler. The aim of pedagogy is to invoke higher-order thinking in students. In this review, we make multiple mentions of 'higher-order' thinking or inquiry. While this is mentioned in alignment with the Bloom's taxonomy [28], we encourage readers to substitute this for whichever pedagogical theory that may suitably apply in individual context. Pedagogy often has inertia and does not evolve as quickly as the latest advances in education research. Ostensibly, the modality in which physics is taught seem to be changing with the adoption of new technologies, however, the underlying principles, methods, and approaches for teaching physics remains largely unchanged [29]–[31].

The traditional and widely implemented lecture-recitation-demonstration mode of lesson delivery has its strengths as a form of didactic teaching. Its iterative nature between rapid content delivery in lectures and rigorous practice in tutorials or recitation classes with immediate feedback allows for the elimination of misconceptions and the quick mastery of taught content; however, it has been criticized for its tendency in turning students into passive learners, who acquire inert knowledge and are unable to apply them to solve real-world problems [32], [33]. The ironic rapid advances in technology, while creating a potential environment for learning through teaching and development activities, is also advancing automation in industries which necessitates a workforce that are able to perform non-routine tasks. Thus, there is an urgent need for current pedagogical methods to fully equip current students with the means of tackling non-routine tasks.

Thus, while traditional pedagogy have successfully led to advanced learning for many centuries, new opportunities in pedagogy must also be provided for students to meaningfully read, discuss and reflect on the content, ideas, issues, and concerns of an academic subject; which can be further enhanced given that we are in a highly technological world and improve computational thinking amongst students [34]–[36]. This begs the question, is it possible to amalgamate modern advances in technology to further enhance the learning process and experience for our students? This review suggests that AR is a potential solution to all these. Multiple studies have shown that the application of mixed reality in teaching and learning can create a more realistic scenario-based and ubiquitous learning environment.

II. METHODS

In order to achieve the desired outcome of this review article, a search for empirical studies and AR design and implementation papers, with the emphasis on recent review articles, was conducted to address questions on how AR can be implemented for physics educational purposes. The methodology is illustrated in the PRISMA flow diagram, Fig. 1.

The following considerations were taken in accordance with the:

1) Research articles, book chapters, conference, and review papers are the main source materials in preparing this review.
2) Resources from the databases of Educational Resource Information Center, IEEE Xplore, Web of Science, Google Scholar and Crossref were included in our literature search.
3) We focused on articles from the past 5 years (2017 to 2021) in order to track the most recent developments. Papers outside of the past 5 years were also included if the information provided is not time-bound. Two rounds of search was conducted.
4) The literature search pays special focus on, but not limited to, the following keywords: augmented reality, extended reality, physics education, visualisation, physics pedagogy, physics teaching, education research.

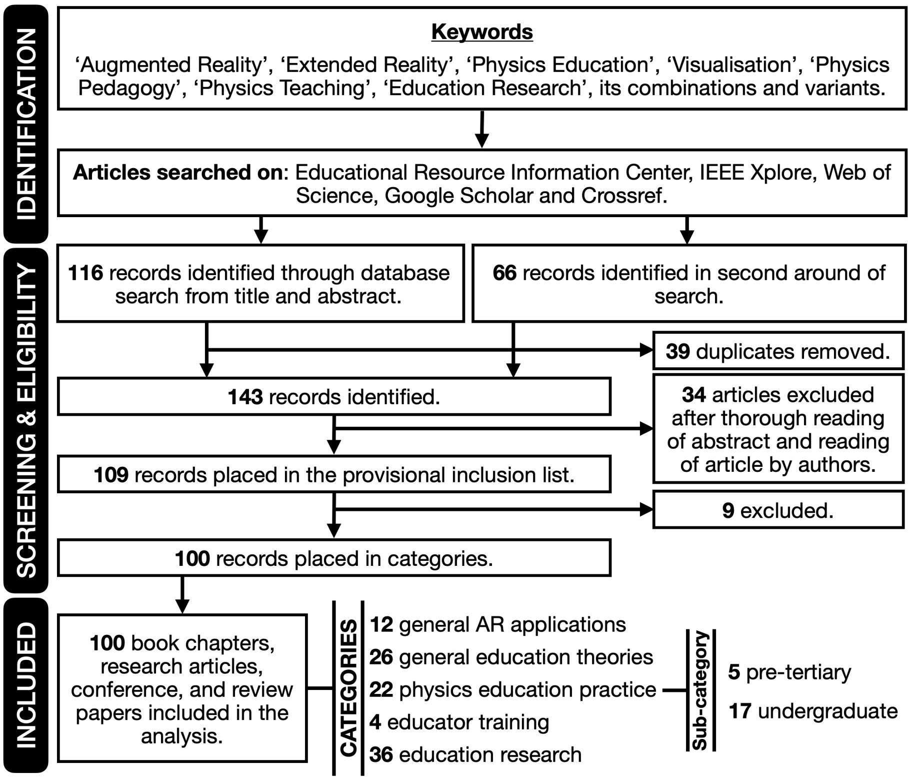

FIGURE 1. PRISMA flow diagram for selection of papers for inclusion in this review.

5) Repeated resources that appear in multiple databases were removed during a first line of screening. The resources not removed at this stage were put into the record.
6) During the second screening process, a thorough read of the abstract/introduction and an inspection of the resources was performed. We did not limit the inclusions to any participant and intervention characteristics, or funding sources. The main exclusion at this stage is due to records that are not AR related or delve into topics beyond the physical sciences. This process was performed by all authors independently before submitting a record of provisional inclusions and exclusions. The list of exclusions that are unanimously agreed upon were then not considered for this review.
7) The provisional inclusion list is then categorised into five categories: general AR usage, general education theories, physics education practice, educator training, education research. Review articles in these categories were specially marked. As there have been many articles written in this domain, our key focus is to find commonality and differences amongst review papers written on this topic. The articles under physics education practice were also further sub-categorised into two education levels, namely pre-teriary and undergraduate (tertiary).
8) The provisional inclusion list is screened for the third time for articles that cannot be placed in any of the categories. These articles are put aside for potential inclusion. A final inclusion list is prepared.
9) The materials identified to be on the final inclusion list were examined for the purposes of identifying opportunities and challenges, which are key in providing perspective to the proliferation and effectiveness of AR in education, in particular physics education, in the long term.

These are the guiding questions adapted from Wu *et al.* [37] and found to be useful for scoping the review. They will be used to evaluate the content of the materials included in this review:

1) What is the framework, theory, or principle that guide the design and implementation of AR in the reviewed papers?
2) How is AR integrated into learning or teaching?
3) What learning outcomes are promoted by AR, are there any identified learning outcomes that AR is unable to achieve?

We identify that there is a potential risk of bias in the included studies, in particular, for studies that fall outside the 5-year range that we wanted to focus on. For these articles, they were included based on their perceived importance in developing the ideas of this article. For example, different educators have their preferred learning taxonomy. In this article we chose to use Bloom's taxonomy as the point of discussing the use of AR in enhancing pedagogical methods. However, we note that other learning taxonomies can be used in place of Bloom's without changing the key ideas of this article.

With the final inclusion list, the remaining of the paper is structured as such: firstly, we study in general, how the infrastructure and implementation of such technologies have led to the success or failure of the use of AR technology in education (Section III) and the various evaluation tools that can be used to judge the success of implementation. Next, in order to facilitate school administrators or educators to critically evaluate the scale of effective implementation of AR technology, we look at how AR can meet the needs of current teaching pedagogy and how modern physics education has been transformed by AR technology (Section IV). We also identify the gaps that AR technology have yet to address. Finally, to advance research in the use of AR in physics education, we conclude with perspectives on how AR physics education research (PER) can expand beyond its current capacity and be the front-runner in the sector of technology-infused education research (Sections V-VI).

III. AR IMPLEMENTATION AND EVALUATION

In a study by Ismaeel and Mulhim [38], they investigated the influence of AR on the achievement and attitudes of student tolerance among undergraduate students. Ambiguity-tolerance/intolerance is a psychological construct that defines an individual's relationship with ambiguous stimuli or events. The study reveal that AR helps ambiguity-tolerant students improve academically and form positive attitudes towards the use of AR in teaching and learning more than their ambiguity-intolerant counterparts. In a separate study, Radu and Schneider [39] found that AR positively affect student engagement, such as aesthetics, curiosity, endurability, focus, interest, and involvement. However, there were concepts where the presence or absence of AR did not affect learning gains. Some students were even confused and had trouble understand AR representations. These findings are important in informing educators of the importance of having a good framework when developing AR for use in the academic setting. A poorly implemented infrastructure and integration into the curriculum will shortchange some students, and may be counterproductive.

As discussed in Section I, AR is a broad-based integration of users, data base, and infrastructure. Thus, regardless of the research intent and question, AR for physics education is only as useful as its implementation approach, pedagogical effectiveness, and friendliness to instructors and students. In this section we discuss literature and suggestions on how to implement AR infrastructure for education purposes and highlight two useful evaluation tools to judge the degree of implementation success of AR.

A. IMPLEMENTATION

The implementation framework of any technological tool used for education requires a synergy between users, both instructor and students, infrastructure (including but not limited to the choice of platform, tools, technology, and manufacturers), and data base management. In this section we look at some framework recommendations from the papers reviewed. The recommendations are arranged according to degree of implementation, from AR as an enhancement tool to a transformation implementation.

1) STARTER KIT

Thomas *et al.* [40] provided a starter tool kits with recommended resources to kick-start AR implementation. We provide the broad steps in Fig. 2.

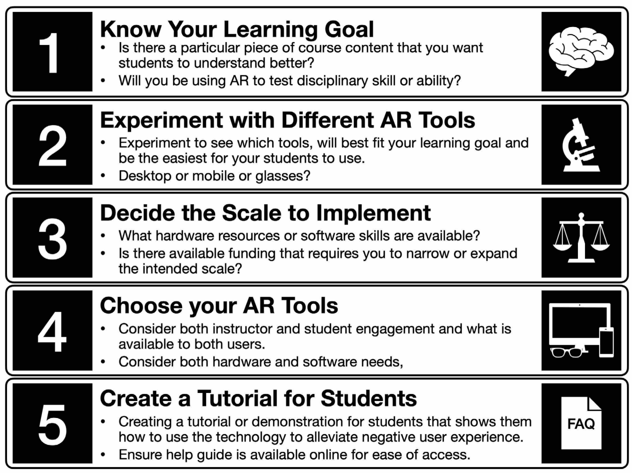

FIGURE 2. Recommended steps taken to kick-start AR implementation as proposed by [40].

2) DESIGN RESEARCH FRAMEWORK

Blended learning, which utilises both online and face-to-face modes of teaching and learning emerged as a result of advancing technologies. Ustun and Tracey [41] recommended a three-phase framework, adapted from a previous model by [42] to implement and spread any educational initiatives. The three-phase approach is illustrated in Fig. 3. One of the many reasons why AR initiatives fail to go beyond topical, ad-hoc implementation is because of the inertia against "redesign of the course" as featured in *all* three phases. AR is often used as intervention or "good-to-haves" without a deliberate purpose of being part of the curriculum. There needs to be a paradigm shift of how ubiquitous learning products and studies are implemented in educational practice. There is a need to combine this paradigm with learning theories, in doing so, it can lead to flexibility of pedagogical models, encourage self-regulated learning, allowing a ubiquitous learning experience [43].

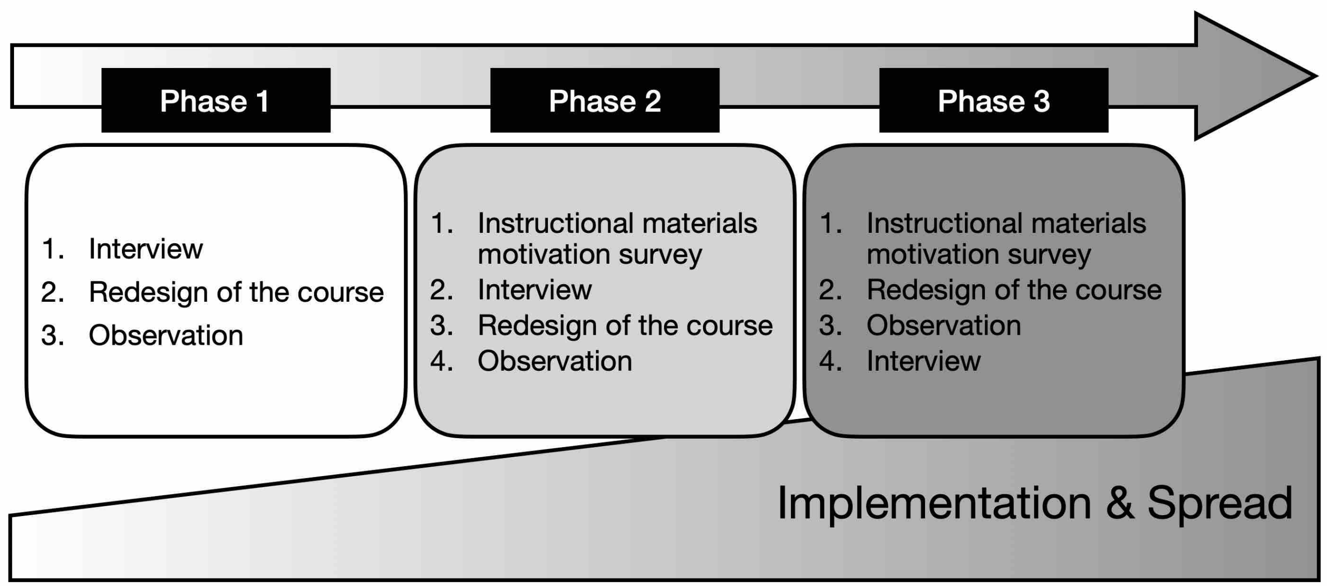

FIGURE 3. Framework for implementing educational technologies through the design research model proposed by [41].

3) INTRODUCING AN EDUCATIONAL ARCHITECT

One of the successful implementations of AR that manages to overcome this barrier is the work presented by Abu Bakar *et al.* [44]. They provided an overview of the process of developing an AR application. For its implementation, a software architecture needs to be developed. These may include database storage, sensors to trigger AR marker or GPS in the case of location AR activation, multimedia objects and/or scenes. Then, in the development process, user interface and experience needs to be rigorously tested so that key features are easily accessible by new users. 3D modelling then takes place, where virtual objects are coded to behave how it should be in the real world. More user testing takes place, this time in the actual setting it is intended to be used. Expert evaluation takes place, where the panel should comprise of individuals not involved in the development process. This is an iterative process.

There are several stages to enhance and transform the teaching and learning experience, these stages will be further discussed in the next section. The most basic level is creating AR-substituted teaching materials. Such materials may include quick response (QR) codes that trigger virtual objects to be displayed when a view finder captures the AR marker [45]. These are easily implementable and form direct substitutes for other multimedia options as the infrastructure is readily available and open source. As discussed in the previous section, these form the majority of current implementations. This is usually where most work stops as more advance implementation often require technical support beyond the technical-know-how of educators.

It is no surprise that, Reeves and Lin [46], and Fernandez [47] identified the gap between the user and infrastructure as a major barrier to adoption of AR technologies in education. In a separate study, Osuna *et al.* [48] identified five present challenges to AR implementation. They are: (i) lack of teacher training, (ii) lack of educational experience, (iii) lack of conceptual foundation, (iv) lack of educational research, and (v) lack of institutional support.

The missing piece of the puzzle is to involve manufacturers and developers of AR infrastructure. Each party has its own technical knowledge, an educator with pedagogy and developers with programming. The main problem is that the developed material is not adapted to the curriculum but is based on experiences that are presumed interesting. Thus, a compatible and nonexclusive approach must be taken. There needs to be a bridge to explore opportunities where AR can be injected into pedagogy beyond the basic level, this task is perform by the educational architect, which can be a person from the institution's pedagogy department [47]. Fernandez proposes a six-step methodology to aid adoption of AR technology and are quintessential elements: (i) training teachers; (ii) developing conceptual prototypes; (iii) teamwork involving the teacher, a technical programmer, and an educational architect; (iv) producing the experience; (v) training teachers to apply AR solutions within their teaching methodology; and (vi) implementing the use of the experience with students. The introduction of a educational architect closes the gap between the expertise from the users and the infrastructure.

We synthesize the framework by Chang and Hwang [49], and Bistaman *et al.* [50], into an illustrative framework and include the role of the education architect in Fig. 4.

4) STUDIO THINKING FRAMEWORK

The studio thinking framework (STF) was introduced by Hetland *et al.* in 2007. They assert that visual arts can have positive impacts on student learning across the

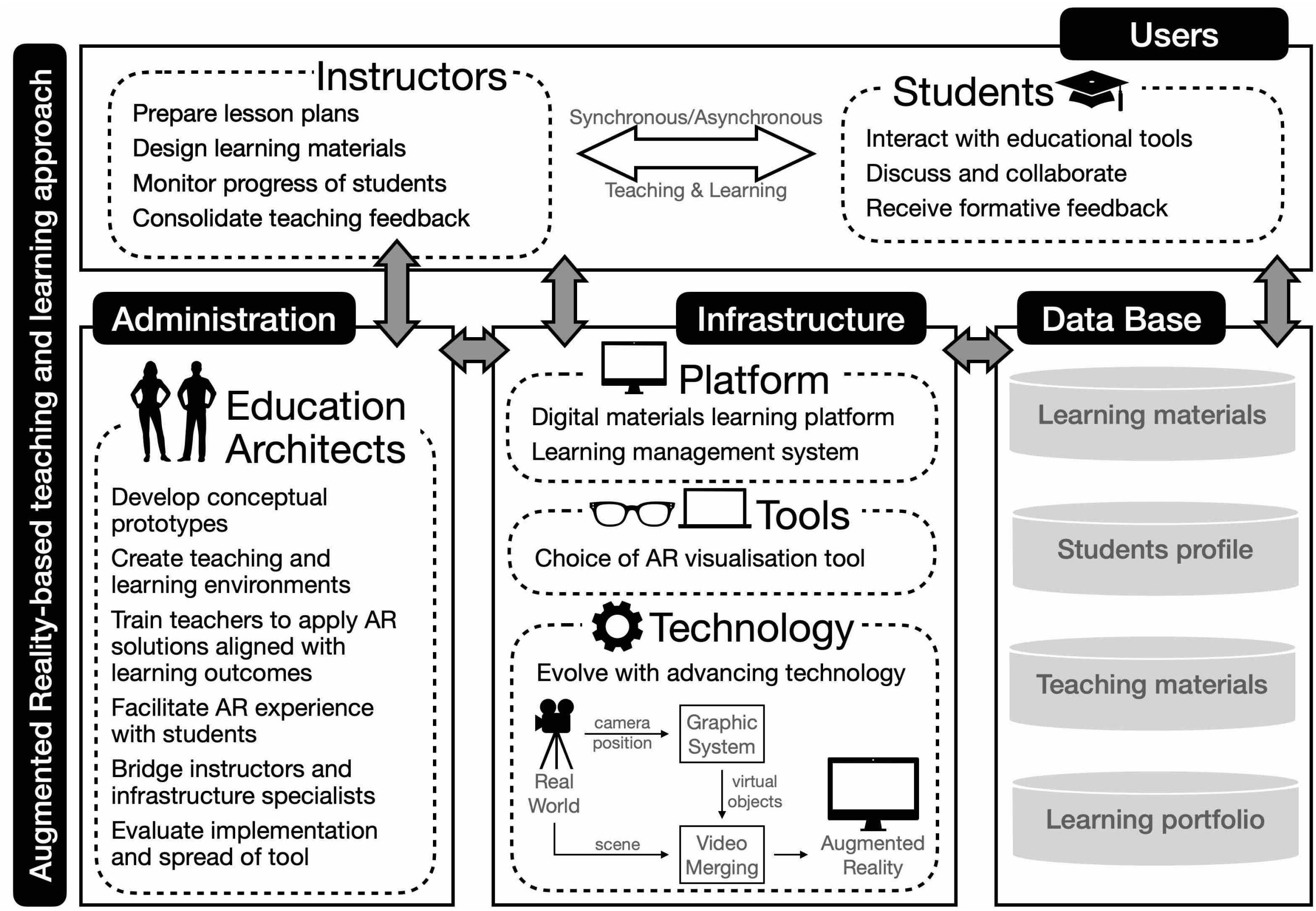

FIGURE 4. Schematic introducing the overarching view of AR and its alignment with pedagogy.

curriculum [51]. STF could help educators in other disciplines learn from existing practices in arts education. Steele *et al.* have successfully implemented it among the social sciences and humanities students and STF is said to be beneficial when brought to physics education [52]. Since cognitive and creative skills are key development skills, coupled with the promotion of reflection, satisfaction, and motivation to explore in STF, the pedagogical implication of STF could include the extension of immersive learning theory as a pedagogical approach, promoting generative learning within the learning environment. AR could be the pedagogical lens to the extent that learners may engage new digitized learning content in certain ways encouraged by STF, such as observe, envision, express, engage and persist, stretch and explore, reflect and evaluate. These are all higher-order inquiry skills in Bloom's taxonomy. The study by Salar *et al.* [53] seeks to investigate AR immersion experiences and its effect on interest, usability, emotional investment, focus of attention, presence, and flow. Although there was no direct mention of STF, these are the same outcomes desired by the framework. They found that intrinsic elements like emotional investment influenced participants' sustained interest of AR. More research can be done in this area to investigate how STF can improve implementation, and further sustain interest in ensuring the longevity of AR in physics curriculum.

B. EVALUATION

In this section, we highlight two useful evaluation tools to judge the degree of implementation success of AR technology, which by extension can be applied to AR implementation in physics education. As these are based on pedagogical grounds, the same evaluation can be used for other technology initiatives.

1) HOLISTIC EVALUATION MODEL

The holistic evaluation tool is a rubric that is adapted from a formative tool originally used to evaluate eLearning tools in higher education. ELearning tools are defined as any digital media, mediated through the use of computing devices to support teaching and learning. The rubric follows our broad definition of AR implementation and it supports a multi-dimensional evaluation of functional, technical, and pedagogical aspects across eight different domains. The rubric is adapted from [54] and found in Table 1, not all rubric criteria may be necessarily applicable.

TABLE 1. Holistic evaluation that can be used to evaluate successful implementation of educational technologies.

Domain	Subdomain	Descriptor
Functionality	Scale	Can be scaled to accommodate various class sizes with the flexibility to create smaller sub-groups.
	Ease of Use	Has a user-friendly interface and it is easy for instructors and students to become skillful with in a personalized and intuitive manner or through training.
	Tech Support/Help availability	Campus-based technical support and help documentation is readily available and guide users in troubleshooting problems experienced; or, the tool provider offers a robust support platform.
	Hypermediality	Allows users to communicate through different channels (audio, visual, textual) and allows for non-sequential, flexible/adaptive engagement with material.
Accessibility	User-focused participation	Designed to address the needs of diverse users, their various literacies, and capabilities, thereby widening opportunities for participation in learning.
	Required equipment	Proper use does not require equipment beyond what is typically available to instructors and students (computer with built-in speakers and microphone, internet connection, etc.).
	Cost of use	All aspects of the tool can be used under funding, at a minimal cost or free of charge.
Technical	Integration within a LMS	Can be embedded or fully integrated into a Learning Management System (LMS) while maintaining full functionality of the tool.
	Operating systems, browsers	Users can effectively utilize with any standard, up-to-date operating systems or browser.
	Additional downloads	Users do not need to download multiple software or browser extensions.
Mobile Design	Access	Can be accessed, either through the download of an app or via a mobile browser, regardless of the mobile operating system and device. Design of the mobile tool fully takes into consideration the constraints of a smaller-sized screen.
	Functionality	Little to no functional difference between the mobile and the desktop version, regardless of the device used to access it. No difference in functionality between apps designed for different mobile operating systems.
	Offline access	Offers an offline mode. Core features can be accessed and utilized even when offline, maintaining functionality and content.
Privacy, Data, and Rights	Sign up/sign in	Does not require the creation of an external account or additional login, such that no personal user information is collected and shared.
	Data privacy and ownership	Users maintain ownership and copyright of their intellectual property/data; the user can keep data private and decide how data is to be shared.
	Data management	Users can archive, save, or import and export content or activity data in a variety of common formats.
Social presence	Collaboration	Has the capacity to support a community of learning through both asynchronous and synchronous opportunities for communication, interactivity, and transfer of meaning between users.
	User accountability	Instructors can control learner anonymity; the tool provides technical solutions for holding learners accountable for their actions.
	Diffusion	Widely known and popular, it's likely that most learners are familiar with the tool and have basic technical competence with it.
Teaching presence	Facilitation	Has easy-to-use features that would significantly improve an instructor's ability to be present with learners via active management, monitoring, engagement, and feedback.
	Customization	Adaptable to its environment, easily customized to suit the classroom context and targeted learning outcomes.
	Learning analytics	Instructor can monitor learners' performance on a variety of responsive measures. These measures can be accessed through a user-friendly dashboard.
Cognitive presence	Enhancement of cognitive task	Enhances engagement in targeted cognitive tasks that were once overly complex or inconceivable through other means.
	Higher-order thinking	Facilitates learners to exercise higher-order thinking skills (given consideration to design, facilitation, and direction from instructor).
	Metacognitive engagement	Learners can regularly receive formative feedback on learning (i.e. they can track their performance, monitor their improvement, test their knowledge).

2) SAMR MODEL

The Substitution, Augmentation, Modification, and Redefinition (SAMR) model, is a four-level approach to deciding how to select, use and evaluate educational technology, first introduced for K-12 education [55], [56]. While its intended use encourages instructors to advance from lower to higher levels by applying various classroom technologies, it can also be used to evaluate a single technological tool (see Fig. 5). The model has shown to enhance and transform teaching and learning through AR [57]. To facilitate readers' understanding and to illustrate applications of SAMR, we include an example of how AR can be evaluated using the SAMR model by considering an example from teaching and learning the photoelectric effect, adapting from a previous PER [58].

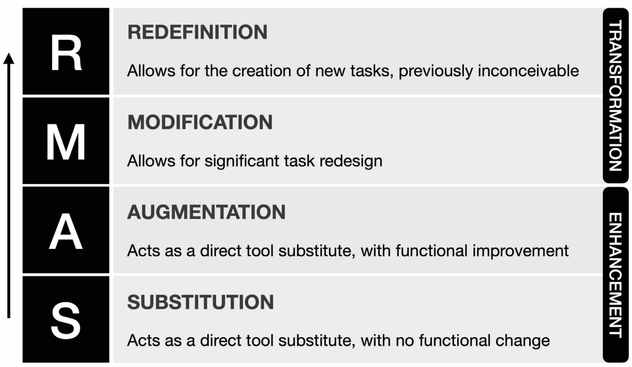

FIGURE 5. Puentedura's [55] Substitution, Augmentation, Modification, and Redefinition (SAMR) model introduced to enhance and transform classroom pedagogy through technology.

The *Substitution* level is the most basic level of the SAMR model that involves enhancement using AR to accomplish the same tasks that does not provide functional change. Students can use mobile AR devices to observe how macroscopic overview of the experimental setup of the photoelectric effect. The use of AR substitutes traditional figures provided in textbooks or drawn figures during classes. It may enhance student experience as it involves placing a virtual object in the real-world through a viewing device, however, it does not change the function of teaching the experimental setup. At the *Augmentation* level, AR changes the function of the teaching material. For example, instead of only displaying the experimental setup, AR can now augment virtual objects like the emission of electrons, this was previously possible only through analog visuals, such as applets. What was previously static images can now be animated, further enhancing and bridging concepts between the experimental setup and electrical circuits. At the *Modification* stage, AR transforms teaching and learning by introducing multiple features and parameters that students can independently change. These might include being able to, toggle between different potentials to observe and interpret concepts relating the maximum kinetic energy to stopping to the work function of a metal; change the number of photons or intensity of monochromatic light and deduce that it has no effect on the stopping potential. Now, the use of AR goes beyond a single purpose of explaining the experimental setup, it can now be used as an actual virtual setup for students to explore. The final step in the SAMR model is *Redefinition*. In this highest level of the SAMR model, students use an AR authoring tool to create experiments which combine their current knowledge with inquiry to create a learning experience that was not previously possible. Here, AR is used to allow participation in learning activities that would not have been possible or would be tedious to implement. For example, building on the previous stage, the AR app can now overlay multimedia content in the form of video demonstration, text and voice explanation and even provide learning checkpoints where questions can be inserted to test learning and provide feedback. The app can also provide students with virtual laboratory tools to create their own experimental setup to investigate their own hypotheses pertaining to the photoelectric effect.

The role of AR changes from a vehicle to present information to a tool that capture and create through mixed reality. These evaluation tools are two-fold, firstly, it allows instructors to evaluate the current successes of implemented initiatives, while reflecting on what is still lacking; secondly, it helps institutions that are looking to incorporate AR elements into its pedagogy to start by considering AR from a broader definition by also including AR design, implementation and integration into both formal and informal teaching and learning environments.

IV. CURRENT AR USAGE IN PHYSICS EDUCATION

AR technology is highly versatile in that it can be implemented across different classroom types: physical or virtual, instructor-led or self-led, synchronous or asynchronous, team-based or individual. More importantly, it allows students to learn without much physical space, time, scope, and resource constraints, without real safety hazards and consequences of failure, and with complete autonomy to pursue their own research questions, experimental designs and data collection. AR has provided a safe learning environment – physically, intellectually, and emotionally – for students to experiment and explore, as well as gain confidence to tackle similar problems in the real world.

A review of educational AR applications, reveal that current research efforts have fallen into two main categories: (i) research projects focusing on practical usage of AR in specific educational contexts to bring new innovations into education, and (ii) education research to investigate the potential of AR usage to measure student outcomes. In this section, we review recent studies with emphasis on lessons learnt from AR implementation for educator training, PER across academic and non-academic domains, as well as the current use of AR to enhance or replace the various pedagogical methods described in Section I.

A. SUPPLEMENTING CURRENT PEDAGOGY

There have been many independent implementation of AR in the classroom demonstration setting. Many of which are useful to deliver topical concepts through technology-based interaction with students in both synchronous and asynchronous teaching and learning environments. For example, there is no lack in research relating to topical implementation of physics phenomena such as kinematics and dynamics [59]–[61], electricity and magnetism [62], [63], optics [64], and thermal physics [23], [24].

A natural evolution of laboratory-based pedagogy is the development of virtual laboratories [65]–[67]. In virtual laboratories, students have the freedom to explore and experiment content within and beyond the syllabus; they remain, however, safe from physical hazards, such as handling corrosive material, radioactivity exposure, and functional apparatus malfunctions. For this reason, virtual laboratories have been

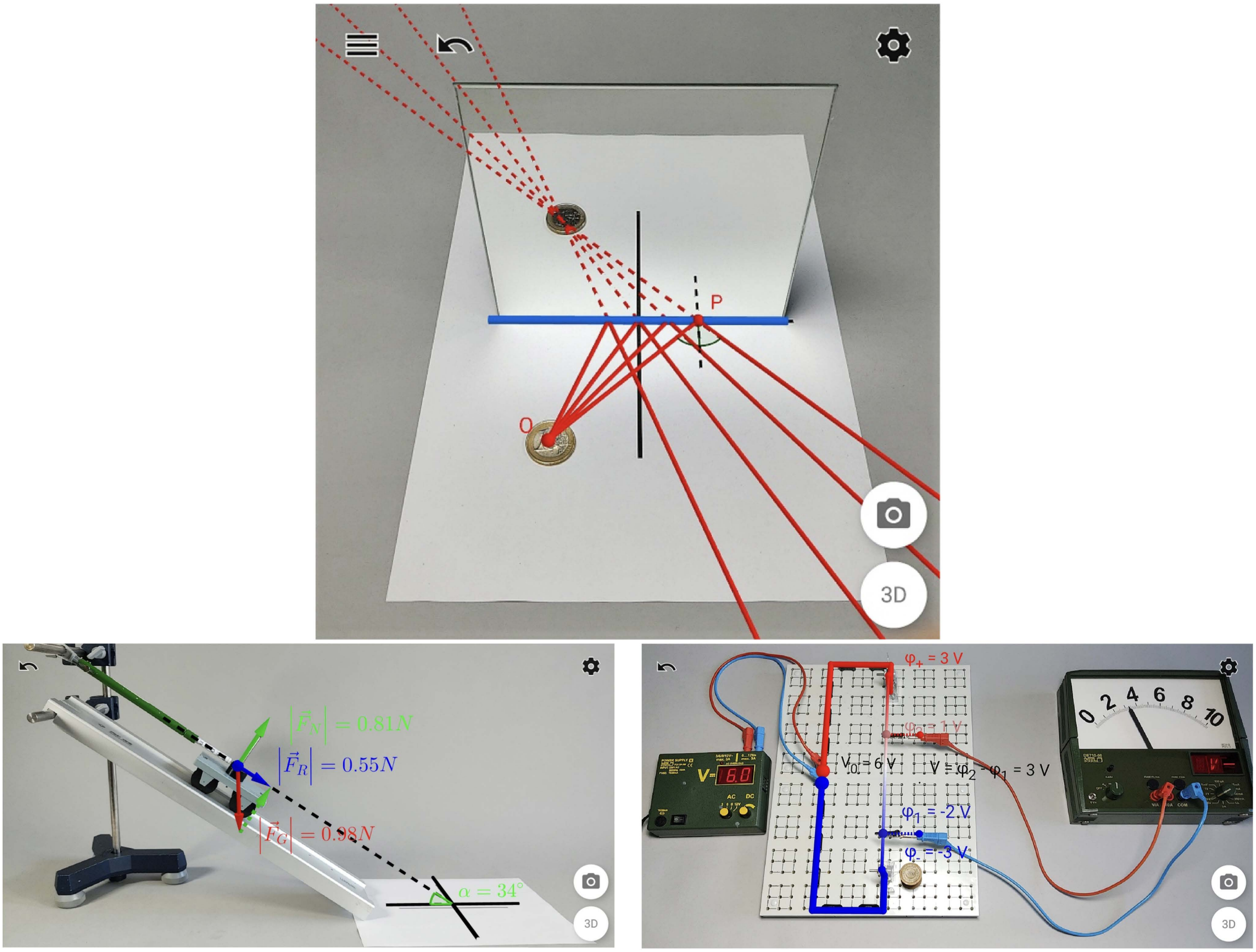

FIGURE 6. Examples of potential use of an AR application, using a mobile phone as a view finder, in physics education to enhance 3D visualisations. Images reproduced from [64] under Creative Commons Attribution 4.0 license.

proposed as a feasible avenue for running safety orientations and introductory courses for new students, wherein safety risks due to inexperience and negligence can be mitigated. The development and utilization of virtual laboratories have seen success when implemented in comparison to physics laboratory [68], [69]. Furthermore, the seamless integration of application-based learning activities can be achieved in the virtual world, in particular those involving apparatus not readily accessible due to cost or training requirements. Simulation-heavy activities can also be integrated easily. With photorealistic and physically-accurate implementation, virtual laboratories can be extremely useful in physics education. However, in order to maximise the potential of AR in enhancing physics education, it would require the need for proper implementation and alignment to teaching and learning outcomes over a sustained period [70]. One of the major criticisms for use of AR in education is the often one-off implementations to measure effectiveness of in topical studies, and may not show the full-depth of invoking higher-order thinking from students. Mostly, this is due to lack of vision and purpose of implementing by the instructor and/or institution. Thus, while it has substituted some teaching materials to achieve basic learning outcomes, it cannot be said that the current use of AR has redefined the way we conduct pedagogy.

B. PHYSICS EDUCATOR TRAINING

Some educators have expressed potential usefulness of simulation-based approaches in tackling complex physics problems in the formal classroom setting [71], [72]. Simulation-based learning involves learning performed in a digital environment, where learners infer concepts based on a simulation model. The purpose of integrating simulation-based approaches through AR into pedagogy is not to replace the instructor, rather, to enhance the teaching experience of educators, and to facilitate teaching. Consequently, educators' familiarity with AR (i.e. its implementation and potential in engaging higher-order thinking) is critical in ensuring successful and long-term implementation.

In the study conducted by Tillman *et al.* [73], all participants were teachers either in-service or transiting into a formal teaching role. They found that all participating teachers were able to create AR concepts to supplement their lesson plans. However, only some of the participating educators' AR concepts actually took full advantage of the affordances provided by AR technology. Sarıgöz [74] and Sural [75] arrived at the same conclusion after studying teacher candidates' response to mixed reality across four domains: affective component, perceived usefulness, perceived control, and behavioural components. Sural showed that participants had good knowledge of mobile devices and fair knowledge of the concept of AR but not AR technology in detail. Both also found that, in particular, science educators are in greater favour of the use of digital technology, including AR, in the classroom. However, Sarıgöz noted that there was some hesitance amongst the participants, attributed to the perceived similarity to computer games and their unfamiliarity with the virtual environment. These effects can be alleviated through familiarity training.

The need for training for educators is supported by Sáez-López *et al.* [76]. The researchers conducted an evaluation study of AR on teacher trainees. They emphasized that AR is not commercially available to the typical student, hence, students do not habitually use this resource in their course of study. Thus, when students are exposed to such technology in the classroom, it often offers certain amount of distraction, and even of time being wasted. From the evaluation data, they were able to propose that once the availability of resources, augmented reality provides benefits and advantages centered on pedagogy that allow for greater enthusiasm on the part of the students, with significant advantages in invoking higher-order inquiry, participation, and motivation. The results underline the need for initial training fro educators so as to be able to design and apply practices with AR in teaching, and to take advantage of the benefits.

There is indeed a potential for the use of AR in the classroom. However, in an environment where the teacher is the person who controls the conduct of the lesson, the teacher needs to be familiar and confident in amalgamating AR into the lesson plan in order for the classroom experience to be beneficial. Teachers also play a wider role in conveying the usefulness of AR to school administration and management. This requires education research into the effect of AR on academic and non-academic outcomes.

C. AR IN PHYSICS EDUCATION RESEARCH

Physics education research (PER) places focus on how physics is learnt with the aim of improving the quality of physics education. Researchers focus on developing an objective means to study the effectiveness, with measured outcomes, of educational interventions, such as the use of technology. In the case of this review, the technology in question is AR.

There is no shortage of studies using AR as intervention tools to study its academic benefits to students' academic outcomes, such as understanding concepts, clearing misconceptions, building skills, and improving test scores. A study by Akçayır *et al.* [77] explored the effects of the use of AR in science laboratories for first-year university students. The group developed AR-assisted laboratory manuals which had embedded video demonstrations. They found that AR positively affected students' laboratory skills as students were not bound to the laboratory to observe demonstrations. Positive outcomes such as shorter completion time, motivation to complete experiments, and willingness to attend laboratory sessions were observed. In the classroom setting, Wahyu *et al.* [78] observed improved scientific literacy among elementary students, with the same observed amongst undergraduate students by Lamb *et al.* [79], and Kaya and Bicen [80].

Pertaining to PER, Strzys *et al.* [24] and Thees *et al.* [26] examined the effects of AR on learning and cognitive load among students in a university physics laboratory course. Both traditional and AR-assisted workflows were investigated during the experiment. The AR condition did not show a learning gain in a conceptual knowledge test, as students were not presented with new knowledge between the traditional and AR-assisted laboratory sessions. Despite this they nonetheless reported a significant lower extraneous cognitive load than the traditional condition.

Cai *et al.* [58] designed a research to address mechanisms behind promoting inquiry motivation amongst students in the classroom, such as the effect of AR on students' efficacy and conceptions of learning. With focus on the wave-particle duality, an intervention study was conducted. They found that by introducing AR into the classroom, students showed significant improvements in understanding of concepts and higher-level cognitive skills. Overall, students also showed confidence in communicating their understanding and expressed inclination towards mastering higher-level concepts, an indication of stimulated motivation to learn. Fidan and Tuncel [81] further incorporated AR into problem based learning (PBL) [82], [83]. They found that students who used AR technology had significantly higher learning achievement scores when compared to their counterparts with teacher-based instruction. This is attributed to the immersive and realistic contexts offered by well-designed AR environments which are able to provide the development of students' cognitive skills and facilitated the transfer of knowledge to real-life environment. Furthermore, the use of AR in PBL was more effective in promoting positive attitudes towards physics subjects than teacher-based instruction. This is consistent with the results from similar studies [21], [77].

Irrefutably, various individual studies have shown improvement in students' academic outcomes, including improved skills and concepts. However, this might not always be the case. For example, a meta analysis by Yılmaz and Batdı [84], synthesizing existing findings from PER investigating the effect of AR on academic achievement, found the impact of AR to be low. Cai *et al.* [85] and Yen *et al.* [86] independently developed AR materials to investigate the efficacy of AR for convex imaging experiment and astronomy, respectively. Both studies showed there was no significant difference between the experimental and control groups in terms of post-test scores. There were researchers investigated the use of AR to enhance the students' learning achievements in science education and found similar results [87]. Though these works were completed in the early 2010s, the consistency of contradictory effect of AR on academic outcomes suggests a deeper relationship between AR and intervention studies. It is important to investigate beyond the academic outcomes and the same works cited, also showed significant improvements to students' motivation towards the topics. Thus, we can conclude, that one of the objectives of performing intervention studies is to investigate the non-academic outcomes.

Bendicho *et al.* [88] studied the effect that AR has on academic procrastination, a non-academic outcome, among engineering student. AR was injected into online assignments. It was observed that there was a reduction was visible even after the students had worked in several tasks before introducing AR. However, it is not possible to uniquely attribute the observed reduction to the novelty effect that cannot be sustained over a long time, or if it is associated with a more intrinsic attraction that students have for modern technologies that helps to reduce academic procrastination more consistently.

Planning, collaboration, teamwork, and communication are some examples of non-academic outcomes. All of which require the motivation to engage, some cognitive understanding of the tasks and the cognitive and emotional capacity to self-monitor and regulate behaviour. Thus, academic and non-acedemic outcomes are usually interwoven. Similarly, optimism and moral and ethical actions can require a complex combination of cognitive interpretation of context as well as motivation to think and act positively. Hence, extending this to PER on the effectiveness of AR, while AR may not lead to significant improvements to post-test scores, the significantly higher motivation in the attention and confidence, is itself a positive outcome that shows the AR can improve students' self-efficacy. The chief outcome of education goes beyond academic success but also to build non-academic outcomes.

D. DEVELOPMENTS BEYOND PER

While many research work focus on the efficacy of implementing AR through PER, there is another field of research that focuses on improving quality-of-learning aspects of physics education through enhancements to AR implementation. The following research have sought ways to enhance the teaching and learning process by considering enhancements to AR usage, beyond targeting academic and non-academic outcomes, by improving on the quality of teaching and learning.

Chandrakar and Bhagat [60] taught real-life projectile problem solving through gamification. The game play involves the user setting the initial velocity and angle. The AR platform augments the target location and the traced path. If the user misses the target location, there will be prompts on screen to improve targeting. A projectile motion question can also be solved natively within the app, after which users can check their answers by performing the exact experiment through the AR interface. Such games allow students to receive immediate feedback, while at the same time visually observing the outcome of their calculations, all within the same platform.

In a separate use of AR in physics, Sung *et al.* [61] aimed to bring realism to virtual representation of motion in the real world through soft body simulations, such as free fall, parabolic motion, and comparison of changes according to object characteristics. They claim that soft body simulation is more realistic than rigid body simulation, so it can be more effective in systems for physics education. While this work is found to be useful and helpful for physics education as it makes current AR simulations more realistic, participants of the research also commented that it did not increase the realism much more compared to previously available material, such as books and videos. Ensuring efficient merging of virtual objects that require high computational resource remains one of the challenges facing the widespread implementation of AR for more advance applications.

Smith and Khechara [89] have attempted to transform students' laboratory experience by providing 'on-demand' information and accessible support through augmented reality in nurse training. This is particularly useful in the physics laboratory environment where it is full of complex equipment and students may be unfamiliar due to the lack of practice. In the absence of an instructor, students might require 'just-in-time' training support to learn. The AR approach adopted by Smith and Khechara included door to digital content accessed by the student through a reader app on their mobile device. Additionally, special tags were added to the laboratory learning space, which included equipment, documentation, chemical reagents. By scanning these tags using a online mobile device, students were provided with additional technical information, safety documentation and tutor recorded demonstrations of techniques and equipment.

The integration of gamification, improved realism, and 'on-demand' information are some developments beyond the objective of improving students' academic and non-academic outcomes. Such implementations are usually successful as they are initiated to improve quality of learning. Thus, these concepts can be widely implemented as they are transferable. It would benefit the physics education sector to look beyond AR applications within PER.

V. OPPORTUNITIES, CHALLENGES, AND PERSPECTIVE ON FUTURE OUTLOOK

To conclude this review, we shall synthesize recent review papers and organise the prospect of AR as communicated by these review articles. Only review articles that provide clearly defined opportunities or challenges are considered, refer to Table 2. After which, we provide perspective on the

TABLE 2. Compiled list of review articles studied that expressed opportunities and challenges for AR implementation in education, with emphasis on physics education.

Review	Opportunities Identified	Challenges Identified
[90]	• Significantly many reported an increase in students' motivation, satisfaction, and engagement with learning environments that are enriched with AR applications.	• Quality of technical services affect the learning effectiveness. • AR used during the teaching-learning processes did not use a wide variety of pedagogical approaches.
[18]	• AR applications to support ubiquitous learning, collaborative learning, and informal learning, how they should be used, and which methods and techniques should be more effective. • Expand for implementation with diverse populations, including students with special needs, and early childhood and lifelong learners. • Directed research toward student satisfaction, motivation, interactions, and engagement. • Conditions relating to potential cognitive overload in AR across various groups should be researched. • Multi-sensory experiences.	• Novelty factor of AR in the classroom often lead positive outcomes, skewing results.
[91]	• Effective AR adoption for classroom instruction shares the common theme that it is pedagogically driven, learner centered, systematic, sustainable, accounts for instructor preparation, and considers the environment of adoption along with the practicality of implementing the technology. • AR offer a uniquely beneficial learning context over traditional electronic learning methods.	• AR is only as suitable as the instructional design and pedagogical constructs used to sustain instruction.
[92]	• In the designing learning and teaching process one of the first operations to be done is to specify learning outcome. AR applications should be fit for purpose and be formed in accordance with the needs as well.	• AR technology suffers from hardware and software constraints such as high resolution, color depth, brightness, contrast, field of view, focal depth, and marker issues. • Absence of technical support greatly affects students' learning experience.
[93]	• Studies can be conducted on less studied sample groups such as students with special needs, preschool students, parents and graduate students. • More utilization of qualitative methods instead of quantitative ones.	• Majority of articles reviewed showed that "undergraduate students" were the most common sample, with preferred sample size "31-100", and surveys were the most utilized data collection tool. • Marker-based AR and mobile devices were used as the main delivery technology.
[94]	• AR can support learning on the physical, cognitive, and sociocultural dimensions • Carry out studies by developing new AR applications for students with special needs	-
[95]	• Studies designed through data collection using the qualitative method. • Studies conducted outside the school or institution, in the informal education setting.	• Articles largely focused on results from the use of AR in the classroom, more work should focus on the implementation phase, which is also part of the pedagogical design. • AR is hailed for its versatility, but few studies consider or support out-of-class activities or usage, i.e blended learning.

development of AR in physics education for the road ahead by consolidating trends from the review papers, lessons from other articles, and observations made from previous sections of this article.

The purpose of providing perspective on future outlook is to leapfrog into frontiers of educational research that few have ventured into; citing Goodwin and Miller on flipped classroom [96], 'if we only implemented strategies supported by decades of research, we'd never try anything new'. The same can be said about AR technology in and beyond the classroom, thus we provide perspective on potential areas of development:

- Based on the trends in educational AR, quantitative methods are most used in educational AR studies. Quantitative methods include studies to identify the effect of AR use on student achievement or to gather student views on AR through Likert surveys or tests. Furthermore, the plurality of studies were conducted on undergraduate students. With the main use being marker-based AR, where users have to point the viewer of their device at a tag or code. While the implementation of AR is wide, it is very much skewed to a certain uniform research methodology. Thus, there exist a gap in research for implementation with more diverse populations. Some of the groups identified were: students with special needs, minority groups, early childhood, and adult lifelong learners.
- Existing development typically concern specific disciplines with a limited range of topics, and the various implementations are extremely disjoint with mutual integration being almost certainly infeasible due to their vastly different AR architectures. Implementations cannot be used across platforms, are not integrated with each other and are often designed to serve a single purpose. There needs to be a unified AR platform satisfying the key indicators of the holistic evaluation model within each institution, so that material can be shared and there is multiplicative effect of effort [97]. Educator groups can be formed in school districts or across institutions to support educators through community of practice [98].
- The majority of AR usage currently in physics education employ the situated learning approach, that is, it is experience-based. There are few studies that showed AR integrated with higher-order inquiry-based learning, collaborative learning, and game-based learning approaches. It is also important to improve students' higher order thinking skills such as problem solving, critical or creative thinking. Educators need to consider how AR can transform with educational benefits as recommended by the SAMR model.
- Current studies are often conducted over a short, investigative period. An education architect can greatly improve AR integration as it bridges the technical expertise that the manufacturer of AR applications have with the pedagogical needs that teachers can spotlight. When integrated, we could potentially see increase in students' motivation, satisfaction, and engagement with the learning environment. The design research framework can systematically motivate implementation and spread of AR in the curriculum over a longer period, while the studio thinking framework can immerse users through other emotive aspect to sustain interest of AR [99].
- AR applications should go beyond the classroom. Future research can investigate the benefits of AR in the context of blended learning, with special focus on out-of-classroom environments and its effect on learning. AR should support ubiquitous learning, collaborative learning, and informal learning. With advancement of the technology, multi-sensory experiential learning can, in the future, be included. In order that AR may be effective as a mediator in the teaching and learning process, there must be administrative reform to school curriculum and teaching and learning environments so that informal experiences of students outside the classroom can also be included [100]. The role of the teacher is to facilitate and be the stimulus for discussion. The gap between formal and informal learning can be bridged using AR in a 'flipped classroom', open, and distance learning approach [101].

These areas of development are not limited to the educational fields described in the articles reviewed. Physics is a subject that encourages the use of sensory and cognitive skills. AR has the a similar goal of integrating the virtual world with our senses. As such a mutual progress in each of these fields can result in collaborative advances in both fields. Moreover, the majority of the articles reviewed in Table 2 gave practical suggestions that can accelerate the advancement of education research in general, which by extension can be implemented for physics education research, with collaboration between technology providers and educators, bridged by the education architect. This section can be found useful by education administrators, management, and the education architect to design educational materials that makes use of advances in AR technology to achieve the intended learning outcomes of physics courses. Furthermore, beyond learning outcomes, AR-based learning technologies is known to strengthen student self-efficacy and promoting higher-level conceptions in physics. Advances in evaluating these outcomes will be useful, not just in students' learning in physics, but also in attitude as a student.

VI. CONCLUSION

In this review, we have comprehensively studied the current use of AR in education, with emphasis on the current implementation in physics education. We pointed out that current implementations are often for the purpose of enhancing teaching materials and learning experiences. However, they have not reached a point where we can definitively claim that AR has transformed the way that physics is taught and learnt. Principally, education research must be supplemented with experiences in teaching and learning environments. Thus, this review also lay out various tools that educators can use, such as the basic starter kit, to more systemic changes for school administrations to consider, like the introduction of the educational architect. By offering a summary of opportunities and challenges as presented by other review papers and proposing perspective on future outlook, we provide possible trajectories for other researchers to seize the opportunities in PER for AR implementation and think of new methods to overcome the challenges ahead, beyond the use of AR to future learning technologies.

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JOEL WEIJIA LAI received the B.Sc. degree (Hons.) in physics with a second major in mathematical sciences from Nanyang Technological University (NTU), Singapore, in 2017. He is currently pursuing the Ph.D. degree with the Singapore University of Technology and Design (SUTD) working on complex systems. He was with the Division of Physics and Applied Physics, NTU, to develop technology enhanced learning tools for teaching courses in physics and mathematics. In 2019, he joined as a Research Assistant with the SUTD–Massachusetts Institute of Technology International Design Centre, SUTD, Singapore.

KANG HAO CHEONG (Member, IEEE) received the B.Sc. degree (Hons.) in applied mathematics from the National University of Singapore (NUS), Singapore, in 2007, the postgraduate diploma in education in education from the National Institute of Education, Singapore, in 2008, and the Ph.D. degree in electrical and computer engineering from NUS, in 2015. He was designated as a University Scholar at NUS.

He was a Grant Program Manager, managing U.S. \$250 M/yr Academic Research Fund at the Singapore Ministry of Education. He was an Assistant Professor at the Engineering Cluster, Singapore Institute of Technology (SIT), from 2016 to 2018. He has been an Assistant Professor with the Science, Mathematics and Technology Cluster, Singapore University of Technology and Design (SUTD), since 2019. His research interests include complexity science, evolutionary game theory, AI in medical and healthcare, active learning, gamification, and virtual laboratories.

He received the SIT Annual Teaching Excellence Award, in 2018, and the SUTD Annual Excellence in Teaching Award, in 2022. He is currently with the Editorial Board of *Journal of Computational Science*. He has served as a Reviewer for more than 20 journals, including *Nature Communications*, IEEE TRANSACTIONS ON PATTERN ANALYSIS AND MACHINE INTELLIGENCE, IEEE TRANSACTIONS ON SYSTEMS, MAN, AND CYBERNETICS: SYSTEMS, IEEE TRANSACTIONS ON KNOWLEDGE AND DATA ENGINEERING, IEEE TRANSACTIONS ON BIG DATA, IEEE TRANSACTIONS ON SUSTAINABLE COMPUTING, *Information Fusion*, *Information Sciences*, and *Physical Review Journal*.