A Survey of Educational Augmented Reality in Academia and Practice: Effects on Cognition, Motivation, Collaboration, Pedagogy and Applications

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***Abstract*— Augmented Reality (AR) technology is gaining popularity and adoption by educational pioneers. While there is great excitement about this technology, there is also a lack of systematic understanding of what makes this technology effective or ineffective for education, and the practical and systemic challenges of implementing it at scale in classroom settings. In this research we provide a synthesis of empirical scientific findings about the factual benefits and detriments of this technology (from a dataset of 2023 academic papers, of which 39 were analyzed in depth), and of public opinions about augmented reality in education practice (gathered from a dataset of 86 websites and blog posts, of which 53 were analyzed in depth). We contribute a list of specific cognitive, motivational and social processes that are enhanced by AR technology. We also identify popular curriculum topics and popular AR applications, as well as summarize several factors that are important for educators to consider for integrating AR into classrooms.**

Index terms—augmented reality, education, affordances, pedagogy, curriculum, learning gains

I. Introduction and Related Work

Augmented Reality (AR) technology and its cousin technology of Virtual Reality (VR) are gaining popularity and adoption by educational pioneers. AR technology combines real-world environments with interactive 3D graphics, such as the ability to see electromagnetic fields around physical objects [1], mathematical formulas in 3D [2], historical depictions of a real neighborhood [3], etc. There is currently great excitement about the potential of AR for educational settings among educators. As seen in a wide variety of blog posts and websites, educators share excitement and futuristic visions, arguing for the potential of AR technology to accelerate student learning, and to transform pedagogical practices. However due to the novelty of this technology, while there is great excitement there is also a lack of systematic understanding of what makes this technology effective or ineffective for education, and the practical and systemic challenges of implementing it at scale in classroom settings. Some empirical data exists in the academic sphere, as researchers have systematically studied the effects of this technology on students in specific contexts, and currently there are many research papers that explore how AR technology interacts with learning processes.

In this research we aim to provide a synthesis of public opinions about augmented reality in education (gathered through websites and blogs), as well as the empirical scientific findings about the factual benefits and detriments of this technology (from academic literature). This synthesis can help teachers, designers, and learning science researchers understand why AR is effective for learning, as well as to have a set of +considerations that teachers and designers can use to create and curate AR-enabled learning environments. In this systematic review we answer the following research questions:

> *RQ1: What are the specific* ***cognitive, motivational, and social processes*** *that are* impacted *by augmented reality technologies in educational settings ?*
>
> *RQ2: For what* **curriculum topics** *could AR provide a benefit, and what are popular* ***AR educational apps*** *that have been used by teachers ?*
>
> *RQ3: What* **factors** *should teachers and students consider when designing or implementing novel AR learning activities & environments ?*

Previous research that synthesized augmented reality literature has focused on factors such as the advantages and challenges of AR in education [4], [5] identified trends and tendencies [4], [6]-[7] and examined different tools and evaluation methods for AR-based educational technology [8]. Although these literature reviews have provided overviews of the uses and benefits of augmented reality, the review literature is lacking an in-depth analysis of statistically significant

978-1-7348995-2-8/22/$31.00 ©2022 Immersive Learning Research Network

findings. Most surveys did not explicitly limit themselves to papers which have a hypothesis-driven experimental methodology - thus, the findings are gathered from various research methods which may not be statistically generalizable beyond specific case studies or informal observations. In contrast, our review investigates specifically only studies that have performed statistical analysis comparing AR to non-AR systems, allowing us to make claims about which specific processes are actually enhanced by educational AR. Additionally, recent reviews focused on a specific use case such as using AR for STEM learning [9], or a specific age group such as primary and secondary school education subjects [10], or a specific learning context such as formal education [7]. Such studies are valuable for understanding the needs of a specific target group but the results are not generalizable to many learning scenarios. Instead, in this survey, we are interested in understanding the effects of AR in general, thus we did not restrict to specific age groups or learning activities. Furthermore, it is important to note that in the literature, there is no consensus on the definition of augmented reality. We have encountered many studies that refer to VR or other tangible and projection technologies as "augmented reality". For this reason, we differ from existing surveys by limiting the term "augmented reality" to specifically match Azuma's [11] criteria that AR applications must (1) combine real and virtual content, (2) interactively respond to user input, and (3) respond to object manipulation in 3D space. Finally, to our knowledge, there is no other literature review that includes websites and blog posts in their review. By doing so, we have gained an insight into the practical perceptions and considerations from public understanding of educational AR, and we reflect on how these compare to findings of actual empirical studies.

II. Methods

For this review our dataset includes academic papers and website posts. Four researchers were part of this process, first gathering all publications, then filtering for inclusion/exclusion criteria, then manually coding them in a spreadsheet, followed by thematic analysis presented in the results.

TABLE I. NUMBER OF RESEARCH PAPERS GATHERED AND EXCLUDED

Step	Papers Excluded	Papers Remaining
Initial Data Collection	--	2023 (Initial)
Semi-Automatic Filtering (Titles)	1532	489
Manual Filtering (Abstracts)	420	69
Full Coding	30	39 (Final)

TABLE II. NUMBER OF WEBSITES GATHERED AND EXCLUDED

Step	Websites Excluded	Websites Remaining
Initial Data Collection	--	86 (Initial)
Full Coding	33	53 (Final)

A. Papers Dataset

To be considered for this review, papers had to meet all the following criteria:

- Published between 2010 - 2021
- Published as peer reviewed conference and journal proceedings papers (i.e. no workshop papers)
- Described an AR system designed for educational purposes
- Presented results of an experimental study involving statistical analysis (i.e. we did not include literature reviews, surveys, or purely qualitative case studies)
- Studied augmented reality (ex: we excluded papers that only studied virtual reality or other technologies), matching Azuma's [11] criteria: (1) combine real and virtual content, (2) interactively respond to user input, and (3) respond to object manipulation in 3D space (i.e. we excluded papers where virtual AR content is simply projected or not tracked in 3D)

Papers were analyzed through a three-phase filtering process (Table I). During initial data collection, 2023 papers were first gathered from proceedings of conferences and journals focused on augmented reality (ex: IEEE International Symposium on Mixed and Augmented Reality; ACM Conference on Human Factors in Computing Systems; IEEE Conference on Virtual Reality; Journal of Computers and Education; etc). We selected publication venues typically associated with ACM or IEEE, and searched material through digital libraries accessible to the researchers' institution, ensuring they meet the inclusion and exclusion criteria below. In the following semi-automatic step, duplicates were removed and titles searched to remove papers not matching our inclusion criteria. In the following manual phase, researchers manually read paper abstracts to further ensure inclusion/exclusion criteria. The full text of the remaining papers was read and coded by separate researchers. The results from the final 39 papers were thematically analyzed.

At the beginning of the manual coding process, researchers commonly coded 15% of papers and discussed any inconsistencies, repeating until inconsistencies were resolved. The final coding scheme included information about the general research design (such as research questions, participant demographics, curriculum and user study tasks and conditions, research metrics), research results (including the type of metrics tested, and which results were statistically significant).

B. Websites Dataset

To be considered for review, websites had to meet all of the following criteria:

- Published between 2019 - 2021, to reflect current applications and trends
- Can be a blog or standalone website
- Described the use of augmented reality for educational purposes
- If discuss AR applications, must focus on more than one AR application and must not be sponsored by a single company (lack of sponsorship was assumed when a website discussed applications from multiple sources; was not hosted on a software development company's website; AND did not specify the page was sponsored).

In this paper we refer to blog posts and standalone websites under the generic term "website posts", or simply "websites". Websites for review were collected through searching publicly available sources. Researchers conducted Google searches for the following terms: ("augmented reality") AND ("teachers" OR "education" OR "classroom" OR "students" OR "learning"). Initially 83 total website posts were reviewed; 33 of these websites were excluded because they did not meet the criteria, resulting in 53 websites for final analysis (Table II). A coding scheme was created to collect information about curriculum topics, names of AR applications, benefits of challenges of using AR in educational settings, what factors teachers should consider when using AR, as well as tips for implementing in learning environments.

III. Results and Discussion

A. RQ1: What are the Specific ***Cognitive, Motivational, and Social Processes*** that are Impacted by Augmented Reality Technologies in Educational Settings ?

TABLE III. Constructs Evaluated by Academic Studies when Comparing AR to Non-AR, and Overall Results

Constructs evaluated by academic studies	Which medium (AR or Non-AR) was generally better?
COGNITIVE PROCESSES	
Content Learning	AR
Memory	Unclear
Cognitive Load / Task Load	Unclear
Attention and Flow	AR
SOCIAL PROCESSES	
Communication & Group Dominance	AR
Guided Exploration	Unclear
MOTIVATION AND USABILITY	
Ease of Use & Overall Usability	AR
Interest & Motivation	AR
Usefulness & Relevance	AR
Confidence & Perception of Self Efficacy	Unclear

In this section we organize our findings in the categories of cognitive processes, motivational processes, and social processes that are impacted by augmented reality technology. We begin each section with a discussion of findings from website posts, where authors typically report firsthand impressions and practical applications from AR applications used in educational contexts. We follow with a detailed discussion of statistically significant empirical results from the academic research literature which have studied specific components and processes and empirically shown whether AR is better or worse than non-AR alternatives. The results of academic studies are summarized in Table III.

1) *Cognitive Processes*

When a learner is engaging with educational content, various cognitive processes can become engaged to ensure effective learning. For example, learner attention may need to be maintained on activities relevant to the learning content; long term memory may be needed to bring background knowledge to conscious awareness, or short-term memory needs to track previous activities; and cognitive load will be influenced by the design of the learning activity. The design of the learning experience, as well as the medium of the experience (including whether AR technology is present or not) will influence the impact on the learner.

a) Results from Websites

The websites dataset provides information about the current public expectations and beliefs about augmented reality. It suggests that AR could have substantial capacity to enhance cognitive processes. Websites mentioned that AR technology's ability for visualizations can enable students to learn faster (mentioned in 44% of website posts); interactivity of AR and the ability for students to "learn by doing" can increase memory retention (mentioned in 22% of websites), and AR can help make abstract topics more concrete (20% of websites). AR can be well suited for project-based learning and simulated learning activities (10% of websites) and recreating past experiences (4% of websites). AR can also benefit through being multisensory (8% of websites), and can lead to improved physical task performance (6% of websites).

b) Results from Academic Papers

The academic research papers dataset provided nuanced empirical findings about the various processes enhanced by AR technology, with results grouped in the following categories:

Content Learning: In the research papers literature, we surveyed experimental studies using quantitative measures to compare educational augmented reality with other traditional methods. It has been found that students who used AR showed better learning performance than the ones who learned through traditional methods such as text [12]-[16], verbal instruction [17], [18], [14], mobile application [19], or web-based learning [20], [21]. Better learning outcomes due to AR have been observed, for example, in math [21], physics [20], [18], [22], [23] and other science topics [19], [12], [15] (also see research question 2 below). However, some studies reported did not find significant differences between AR vs non-AR groups in geometric analysis [15], theoretical physics questions [20], reading and spelling [24], or learning language [25]. This indicates that for some topics AR technology is not better than more traditional approaches. Furthermore, some studies found that using AR can result in worse learning performance in specific areas, for instance, understanding the relationship between physics concepts involving kinesthetic forces [22], [23].

Memory: Memory performance measures can give us insight into what has been learned in an activity and what has been retained in the long term. Since AR learning experiences have shown to be more motivating and engaging [26], [19]-[21], [27], [28], one would expect the experience and the content to be more memorable. However, studies measuring memory performance have failed to find a significant difference between AR and non-AR groups, for example, in measuring the number of words [25] or paintings recalled [29]. On the other hand, [13] found that a 3D tangible interface was more effective for memorization than using 2D paper representations. Based on these results, we can infer that simply visualizing things in AR might not be enough to increase memory performance.

Cognitive Load / Task Load: When introducing new technologies into a classroom setting, it is important to ensure that the students 'working memory resources are not used up by the complexity of the application. Using AR has been shown to reduce the physical and cognitive demand of a learning task [30], [31] by freeing the learner's hands and removing the need to switch back and forth between the physical objects and the learning content, which is overlaid on top of the physical world in AR. On the other hand, the physical demand of using an AR headset was shown to be higher compared to using a desktop PC [1] possibly because of carrying the weight of a headset and lack of familiarity with the interface, which increased the task load. However, these results vary among the nature of the task, as research in [32], [19] showed that using an AR HMD may not provide extra advantage in reducing the cognitive load, and found no significant difference between AR and nonAR groups.

Attention and Flow: Psychological flow is a state of being present, attentive and engaged with the learning content, and such a state leads learners to feel pleasure, dedication and perseverance in the learning activity [33]. AR learning content has been shown to be more effective than non-AR alternatives when measuring student attention, involvement and focus [21], [19], [34], [22] and when measuring flow [20]. However, the impact of AR on attention was not significant in one study [34] comparing AR to video recordings, indicating that the effect depends on the type of user experience.

2) Social Processes

Learning in group settings can be effective because collaborative learners are able to solve more complex problems than they would individually, they can persevere for longer periods of time, and can engage in peer teaching activities that allow them to reinforce and check their own understanding. In this section we present results about AR technology's impact on social processes.

a) Results from Websites

From the websites dataset, the benefits of AR is believed to be potential for increased collaboration and communication skills (mentioned in 16% of websites), improved safety and security in learning experiences (14% of websites), and the ability to connect students at long distances (14% of websites). Additionally, AR may enhance learning accessibility (10% of websites) since it does not depend on books or supplies, and in many cases is cost effective in comparison to VR (10% of websites). However, hardware is believed to be expensive to make available to all students (18% of websites), and AR can be difficult to implement without outside assistance or training (20% of websites).

b) Results from Academic Papers

The academic papers dataset provided empirical perspectives on AR's ability to support group collaboration, in the following categories:

Communication and Group Dominance: Research papers indicate that augmented reality can be useful to help collaborators externalize their thoughts by creating annotations into the real world, or by having external representations to ground their communication. AR was found to benefit communication processes. For example, in [23] it was reported that groups who used AR typically communicated by referring to the external representations provided through augmented reality, rather than creating new ones through drawings. AR groups also spent more time teaching each other than non-AR groups. Similarly, in [27] AR reduced the dominance exhibited by strong leaders and caused more balanced group dynamics. However, in [35] there were no significant differences found between AR vs non-AR groups, when studying the number of help requests initiated by participants, indicating that for some contexts AR does not make a strong difference to communication.

Guided Exploration: When groups have access to more information about a problem (through augmented reality displays or any other technologies), this availability of information may encourage groups to ask more questions because more aspects of a problem become more salient. For example, in [23] and [22], it was found that augmented reality was better than non-AR technology in improving task time, whereby AR groups completed the task faster. However, in [22] it was also found that AR groups ignored parts of the learning content, and also didn't use as much of the physical tools available compared to the non-AR groups. This hints at the possibility that AR visualizations focus the learner's attention on information that is displayed, but may detrimentally cause learners to not use all of the tools available at their disposal.

3) Motivation and Usability

When users feel motivated to engage with a learning activity, and when the interface is learnable and easy to use, they are likely to persist in being present with the learning content even when faced with challenges. On the other hand, when the user experience is lacking and users are not motivated to engage, then users may not engage with the full content and the possible learning benefits may be lost.

a) Results from Websites

Examination of the website dataset revealed consistent beliefs that AR may be effective in increasing student motivation. 54% of websites mentioned that AR has the capacity to make learning more interesting, fun, and engaging. Specifically, students may be able to take on a more active role in their own learning with AR, and learning may become more personalized through the adoption of AR. The potential for gamification in AR and the ability to introduce interactive puzzles/quizzes can enhance homework assignments and make tests more engaging by presenting students with 3D models.

b) Results from Academic Papers

Academic literature provided more nuances on the dimensions of motivation and usability in the following categories:

Ease of Use and Overall Usability: From the academic papers, research that has shown that when users are asked their subjective perception about AR experiences in contrast to non-AR alternatives, the AR experiences were typically experienced to be overall better [36], [12], [18], [31], and specifically more easy to use [16], [36], [37], more learnable [30], [34], more responsive [36], or comfortable [30]. The reason for these results may be that AR is intuitive to use: a user simply moves their body or the augmented objects and observes the effects from three dimensions; in contrast, learning through desktop PCs requires understanding of mouse and keyboard interactions, and paper/video instructional media is not responsive to user actions. It is worth noting that in some cases AR was not statistically different from non-AR alternatives when comparing on factors such as overall usability [25], ease of use [36], [1], or responsiveness [36].

Interest and Motivation: Augmented reality experiences can be highly motivational and engaging, in part due to the novel experience of observing 3D content mixed with real objects, and due to the interactivity and personalized learning that is permitted by digital experiences. Interest and motivation has been measured through a variety of metrics, such as in studies that show AR users, when compared to non-AR users, feel the experience is more fun and motivating [26], [19]-[21], [27], generates higher satisfaction [21], [16], [19], [38], [34], more curiosity and interest to engage for longer [27], [28], feels more aesthetically and visually pleasing [36], [22], and creates more endurability [27]. In a few studies, no significant results were found when AR to non-AR desktop interfaces in terms of challenge [20], [1] or frustration [1].

Usefulness and Relevance: Beyond the short term motivational effects, being able to see the usefulness and relevance of a learning experience can make students have a more meaningful experience that personally engages them and even encourages transfer to other contexts in their lives. Learners feel that an AR experience is more relevant than non-AR approaches [21], [19], more useful [16], [38], and generally more preferred [30], [37].

Confidence and Perception of Self Efficacy: When students gain confidence and feel their skills are high enough to be effective at doing a task, then they will want to engage and persevere with a learning experience. Such confidence and self-efficacy do not merely influence the short term engagement with an experience, but also have potential to change student career paths. Compared to non-AR approaches, AR has led learners to feel higher confidence [19], [34] and higher self-efficacy [22], [23]. However, some studies did not find significant effects in some metrics of confidence or curiosity [21], [22], and in one study it was found that perceived performance in AR was lower than in a desktop-based alternative [1], indicating that differences in design and usability can hinder student self perceptions.

B. *RQ2: For What **Curriculum Topics** Could AR Provide a Benefit, and What are Popular AR **Educational Apps** that Have Been used by Teachers ?*

In this section we present the wide variety of curriculum topics and popular AR applications that have most frequently appeared in our dataset. Table IV shows the most popular curriculum topics applied to AR according to websites (Table IV left) and research papers (Table IV right). When counting the number of websites mentioning a specific curriculum topic, we found that some websites referred to a specific science field (ex: "physics"), while others mentioned "science" in general; for this reason, when reporting the popularity of curriculum topics in Table IV, the sub-fields of science do not add up the total percentage of websites mentioning science. One common theme between academic papers and websites is that Science ranks the highest among all the curriculum topics AR is being used for, and Medicine/Biology topics are highly popular in common, while Language and Literacy appears relatively popular in both datasets. Interestingly, Physics was popular for research papers but not highly cited in websites; while Anatomy and Space were popular in websites but not in research literature. Furthermore, using AR as an Authoring Tool was highly cited in websites indicating a strong need for authoring tools by students and teachers but was not popular in AR research. Other topics differed in popularity, for instance websites Math, History and Art while papers do not cover these deeply. One possible explanation is that most applications in websites are mature applications for students, while academic research tries to explore experimental possibilities that might be difficult to implement in classroom settings.

TABLE IV. POPULAR CURRICULUM TOPICS IN WEBSITES (LEFT) AND IN ACADEMIC PAPERS (RIGHT)

	% Sites
Science	52%
Anatomy	16%
Space	10%
Medicine	10%
Chemistry	8%
Biology	6%
Astronomy	4%
Geology	2%
Physics	2%
Botany	2%
Authoring Tool	26%
Math	22%
History	18%
Art	16%
Foreign Languages	12%
Virtual Field Trips	10%
Physical Training	8%
Reading	6%
Computer Science	4%
Writing	2%
Manufacturing	2%
Geography	2%
Logic	2%
Journalism	2%

	% Papers
Science	36%
Physics	14%
Biology	10%
Anatomy	3%
Astronomy	3%
Aerospace	2%
Environment	2%
Language and literacy	7%
Coding	2%
Science museum	2%
Graphic design	2%
Library	2%
Geometry	2%
Warehouse operation	2%
Archaeology	2%
Artifacts	2%
Social emotional learning	2%
Makerspace	2%
Logistics	2%
Art museum	2%
Factory machine tasks	2%

Table V presents the most frequently mentioned AR apps from the websites. The most commonly referenced apps are authoring tools such as CoSpaces Edu (16% of websites) which is a platform utilizing AR to support 3D creation and coding skills for children and teachers; Merge Cube (10% of websites) which is a platform and kit for accessing educational AR simulations; Metaverse (10% of websites) allows teachers and students to gamify learning through the creation of interactive content in AR; and Moatboat (10% of websites), a speech-based creation engine. Other top popular apps include Catchy Words AR (10% of websites) which presents a word game used to enhance vocabulary learning in early childhood; and Curiscope

(10% of websites) which enables students to learn about the human body and other STEM topics by utilizing AR visualizations on t-shirts and classroom posters. Notably, all these applications are able to be used on mobile or tablet devices, which may make it easier for teachers to use in a classroom setting, as no other bulky or expensive equipment is required.

TABLE V. POPULAR AR APPLICATIONS APPEARING IN WEBSITES

AR App	Curriculum / Content	% of Sites
CoSpaces Edu	Authoring	16%
Merge Cube	Authoring & Simulations	10%
Metaverse	Authoring	10%
Moatboat	Authoring	10%
Catchy Words AR	Word Learning	10%
Curiscope	STEM	10%
3D Bear	Authoring	8%
World Brush	Art	8%
Anatomy 4D	Anatomy	6%
Elements 4D	Chemistry	6%
Experience Real History	History	6%

C. *RQ3: What **Factors** Should Teachers and Students Consider when Designing or Implementing Novel AR Learning Activities and Environments ?*

Educational applications contain specific design features, and they typically exist within a larger context. Thus, multiple factors may contribute to their success. Our analysis of websites revealed the following topics for considering in designing AR for educational settings:

Accessibility: The most discussed barrier to consider is whether AR experiences require expensive hardware or complicated software, this issue being mentioned in 18% of websites. While there are a lot of AR applications that can be run just with an internet-enabled smartphone or tablet and no other hardware, some apps are only available in certain operating systems or have certain technical requirements such as camera quality or OS versions. The availability of devices that match with software could be expensive for enabling a whole classroom. Additionally, some AR applications require purchase of physical objects - for example, Merge Cube provides a low-cost solution using a physical cube, but to gain a better experience, students can purchase an AR headset holder. Providing such standardized hardware for whole classrooms can be challenging.

Technology evolution: Some augmented reality apps are still in the development stages and are still working out bugs. Wherever possible, teachers should aim to test out the app themselves first to make sure they feel comfortable using the system and that interface problems will not interfere with students 'learning experience. Additionally, we found that research papers covered a variety of AR technologies; among the most popular are mobile devices (38%), head mounted AR displays (36%), desktop computers (18%). On the other hand, the scope of AR technology in the websites is very narrow, whereby 96% of the websites talked about AR applications with smartphone and tablet devices. This indicates there is a gap between what is being researched vs. what is actually used in the classroom. More efforts and investment are needed in order to convert experimental AR research technologies into practical applications for classrooms, and as technologies evolve (ex: smartphones with 3D cameras) we will see more complex applications in classrooms.

Space requirements: Some of the websites discussed the physical space needed for the experience. Many AR apps require open spaces where digital images can be projected into the real world, and where students can move around to see the content from different angles. Some applications even require walking around in a large space, or being outside where GPS signals can be used. These requirements limit the contexts where AR applications can be used.

Teacher support: Not every teacher or student is technology savvy. 6% of the websites pointed out that teachers should consider the level of difficulties to implement or to integrate the AR experience into the classroom environment and into the curriculum. For example, one teacher said despite the extensive support from her school's administration and IT department, there were technical issues with the school firewall blocking the applications. Beyond software reliability, some websites discussed how teacher and student training is vitally important, and others mentioned the need of an ecosystem and support from others to develop good ways to teach with this new technology.

Suitability to audience and goals: Teachers should choose the apps that are suitable to students needs, curriculum and teaching goals. Individual learners may respond very differently to using AR, and some students may get distracted from the learning content by the AR experience itself. Teachers should continuously monitor students 'experiences when using AR and provide additional supports where necessary. Depending on the age and general purpose, the functions of the apps can differ widely; for example, 3D Bear claims they are for ages 3-17, while Merge Cube is more appropriate for age 10+. Some websites also mentioned it is important to help students differentiate reality from virtual content, especially for younger students who may not understand that they are seeing a simulation.

Pedagogical approaches: Some of the websites mentioned using AR for remote learning, whereby students can use the applications at home on their own devices. Also, in many instances AR may prove more useful as a supplemental instructional tool rather than as a primary means of instruction. Teachers should consider how to pair AR experiences with other instructional practices, and how AR may transform practices. For example some websites mentioned that the teacher will become more of a "guide on the side" rather than the traditional "sage on the stage". Finally, some websites proposed the possibility to combining AR and VR applications, as they can be used for different purposes (AR to extend current physical objects and places, and VR to transport students to different places).

Contextualizing the content: When choosing which application to use, teachers need to think about what goal they are trying to reach with this technology, and how the technology can support this goal. It is important to be aware that AR (and VR) content can be overwhelming for students to process, and that each student may take a personal path through the learning content. Therefore it is important to support students in setting expectations and contextualizing engagement beforehand; and, after the experience, to reflect as a whole class on what students experienced and how it ties to the curriculum.

IV. CONCLUSION AND LIMITATIONS

This research provided a synthesis of public opinions about augmented reality in education (gathered from a dataset of 86 websites and blogs, of which 53 were analyzed in depth), as well as the empirical scientific findings about the factual benefits and detriments of this technology (from a dataset of 2023 academic papers, of which 39 were analyzed in depth). We identified specific cognitive, motivational and social processes that are enhanced by AR technology. We also identified popular curriculum topics and popular AR applications, and we have summarized several factors that are important for educators to consider for integrating AR into the classroom.

We acknowledge two limitations about the generalizability of these findings. First, a part of the dataset is generated from websites that contain popular opinions and expectations; these are not scientifically measured findings, and should be followed by rigorous studies. Additionally, the review findings are highly contextual: first, the academic research is typically done in controlled settings where the results may generalize only to similar contexts that contain similarly-controlled variables; and second, the current popular subjects and applications of AR are generated from applications that have specific designs, thus it is possible that other applications in the same domains may yield different results. While these results indicate general directions where AR may be beneficial or detrimental, these results may change as different applications are developed and evaluated under varied conditions.

V. ACKNOWLEDGEMENTS

This material is based upon work supported in part by National Science Foundation under grant no. 1917716.

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