REVIEW
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A Review on Augmented Reality Authoring Toolkits for Education

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Creating pedagogically sound, interactive Augmented Reality (AR) experiences supporting situated and experiential learning remains a challenge to teachers without programming skills. To integrate AR in the everyday classroom, teachers need to be capable of designing their own immersive experiences for their students, which is why an analysis of existing authoring toolkits is necessary to identify suitable tools for educational application development and future research directions in terms of educational AR. We identified "easy access", "GUI-based design", and "interactive contents" as needs of teachers for designing AR content for the classroom. Based on these needs, we conducted a literature review of 835 documents. Of 80 relevant articles, we included 43 peer-reviewed articles from ACM Digital Library, DBLP, IEEExplore, Scopus, Web of Science, Google Scholar, and miscellaneous other sources in our analysis. We identified 69 different AR authoring toolkits and classified these with regard to their accessibility, their degree of required programming knowledge, and their interactivity. The results show a divergent research landscape with a lack of empirical evaluation. Of 26 openly accessible toolkits, we identified five toolkits addressing the defined needs of teachers for designing interactive AR experiences for the classroom without requiring extensive programming knowledge. We conclude that there are only few tools for the straightforward design of educational AR experiences addressing the needs of teachers and suggest using research-informed and evidence-based criteria for developing AR authoring toolkits for education.

Keywords: Augmented reality, immersive learning, authoring toolkit, technology-enhanced learning, augmented reality learning

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1 INTRODUCTION

Even before the inevitable digital changes in educational teaching and learning arrangements due to the global pandemic, a high interest in immersive technologies such as Virtual Reality (VR) and Augmented Reality (AR) could be observed among users (Cipresso et al., 2018). Regarding the role of immersive media in technology-enhanced learning, the high prevalence of smartphones and tablets in students' everyday life (Südwest, 2018, 2020) makes the use of low-immersive AR (Iqbal et al., 2021) interesting for teachers. While the affordances and benefits of AR in educational settings are already well-researched (Dunleavy et al., 2009; Chang et al., 2011; Billinghurst and Duenser, 2012), the creation of such tools remains a challenge for the everyday (digital and real-life) classroom. Even though there is a large number of AR authoring toolkits supporting the creation of such applications, the development process can be tedious for teachers without prior programming knowledge as many toolkits still require a considerable amount of scripting. Concurrently, research has shown that interactive AR applications, in particular, can support experiential and active learning (Huang et al., 2016; Moorhouse and Jung, 2017; Jesionkowska et al., 2020), which makes such experiences highly desirable. Although current eXtended Reality (XR) educational systems focus on specific immersive media technologies, the path to optimising the use of XR in education would be easier to navigate through the provision of adequate authoring toolkits, which is the motivation of the research described in this paper. It has been proven that XR has the potential to assist educators (Kosko et al., 2021) in transcending the physical boundaries of lecture theatres, labs and classrooms; there is a need to evaluating the effectiveness of existing authoring toolkits to create and deliver quality content and XR learning experiences. The development of XR authoring toolkits involves an iterative software development process (Dodds, 2021), while current XR educational developments focus on specific test scenarios with high expectations in programming skills (Yang et al., 2020).

Freitas et al. provide a summary of existing AR authoring toolkits. They identify five challenges addressed by various toolkits with a special focus on rapid prototyping (Freitas et al., 2020). Another review was carried out by Nebeling and Speicher (Nebeling and Speicher, 2018) on tools for 3D design and programming of AR and VR experiences, resulting in five categories focusing on required skills/resources and levels of possible fidelity. While these reviews include valuable insights, an educational focus on AR experiences is still lacking. To the authors' knowledge, there is no literature analysis reviewing the suitability of AR authoring toolkits for developing educational experiences. Therefore, the rationale of this review is, building upon the findings of Freitas et al. as well as Nebeling and Speicher, to not only integrate more recent tools into the analysis, but also to investigate the following research questions:

1. What is the current research landscape on AR authoring toolkits?
2. What are the characteristics of these authoring toolkits regarding their accessibility, required level of programming skills, and developmental capabilities?
3. Which of these authoring toolkits are suitable for teachers to create educational AR experiences for the classroom?

Throughout this paper, we will explore the research questions based on a systematic literature review covering relevant databases with suitable search, inclusion, and exclusion criteria. These research questions are designed to illustrate what lies ahead in terms of the role of authoring toolkits for the design of educational AR experiences and the search process, and results are presented. The findings are discussed and implications for future research and development endeavours are drawn.

Additionally, the perspective of the scientific reception of existing authoring toolkits is presented, which is the current research gap in the area of XR educational authoring toolkits, as our aim is to provide evidence-based perspectives on the available toolkits rather than comparing their technical features (although the technical features define the functionality available to the educators).

2 DESIGN OF AUGMENTED REALITY IN EDUCATION

Park states that "[t]he primary purpose of AR toolkits and frameworks is to reduce tedious and time-consuming work common to most AR applications" (Park, 2010, p. 727). The development of an AR experience, as a combination of the real and virtual through interactive objects in a 3D environment (Azuma, 1997), requires tracking sensors, user movement tracking, techniques for modeling 3D objects, and inertia (Van Krevelen and Poelman, 2010). Due to these characteristics, there is a lack of tools to quickly iterate and create new ideas utilizing low fidelity prototype methods, which leads to the first requirement for educational AR authoring toolkits: easy accessibility.

McIntyre et al. identify eight problems in the AR prototyping area: the lack of simple coding environments for AR, lack of resources needed for the creation of 3D content, dealing with multiple unrelated tracking technologies, lack of resources for sensing and reasoning technologies, lack of separation of concerns between system components, difficulties in the relationships between physical and virtual worlds, developing in the physical world, and working in real-time (MacIntyre et al., 2005). Nebeling and Speicher highlight three similar problems: a massive tool landscape, requiring tools from multiple classes, and significant gaps of tools within and between classes of tools (Nebeling and Speicher, 2018). The collaboration between end users, authors and personalization are also important features to be considered in the authoring tools in AR with zero programming for educators (Vert and Andone, 2017).

Due to these problems, Nebeling and Speicher discuss how authoring tools can facilitate the creation of rapid prototypes focused on 3D content, interactions, scenes, and mobile screens (Nebeling and Speicher, 2018). They structured existing authoring tools into five classes according to the skills and resources required as well as their possible level of fidelity. The first class, *Basic Mobile Screens & Interactions*, comprises tools such as InVision, Sketch, and Adobe XD, which allow the concept of multiple screens and supporting active regions in these screens together with mouse interactions. The second class, *Basic AR/VR Scenes & Interactions*, creates basic forms of AR/VR content with interactive behavior, for example uploading 360-degree photos and creating immersive, interactive scenes (includes toolkits such as DART, Proto. io, Halo, and HoloBuilder). The third class, *AR/VR Focused Interactions*, focuses on AR camera-based interactions using markers. Toolkits of this class are for example, ARToolKit, Tiles, Studierstube, and ComposAR. The fourth class is called *3D Content* and describes all 3D content creation tools such as Teddy, Lift-Off, Google's SketchUp, and Autodesk's 3ds Max and Maya. Tools in this class allow the digital creation of new 3D objects. The fifth class is *3D Games & Applications*. This class includes comprehensive game engines such as Unity, Unreal, and AFrame. Visual editors are integrated into most of these toolkits. Nebeling and Speicher point out that most toolkits that enable the design of AR/VR scenes with low programming knowledge do not support 3D modeling or explicit interaction at the same time (Nebeling and Speicher, 2018).

Freitas et al. report five challenges regarding the rapid authoring of AR experiences and toolkits addressing these challenges. The challenge *3D Objects* (expensive and time-consuming creation of 3D content) is addressed by tools such as Clay, ProtoAR, Vuforia, Unity, and Cinema 4D. A second challenge, *Gesture*, focuses on interactions with gesture definitions, e.g. toolkits like GestureWiz, Wizard of Oz, and Sketch. The challenge *Validated Interactions* is addressed by Wizard of Oz, WozARd, ProtoAR, DART, MockAR, Lake, PowerPoint, Keynote, and Sketch. *Camera Simulation* challenges can be focused with a 3D printed smartphone frame or video simulations. The *Communication of Concepts* can be carried out with paper (such as stick notes), the Storyboard tool, 3D-HUDD, videos, and PintAR. Real time environment tools include Wizard of Oz approaches, WozARd, Lake, Unity, and Xcode (Freitas et al., 2020). It must be noted that Freitas et al. analyzed not just AR authoring toolkits but also 3D design software.

There has been an increase of rapid software development tools for AR applications within the past decade in general also for AR authoring toolkits as well. A common problem of some of these toolkits is that the use of existing code libraries results in big, monolithic systems creating complexity in usability. Object-oriented approaches found in newer development tools can provide a more flexible and component-based approach to fast prototyping. But still, these AR authoring toolkits focus on the main AR functionalities for better interaction rather than storytelling and scenario simulation, which would be greatly needed in educational settings for creating more productive results. This leads to difficulties in using the toolkits and frameworks, especially for new developers, novice programmers and people without computer science background (Park, 2010).

As this is the case for most teachers, where very few have any computer science background, this systematic literature review focuses on this target group and investigates AR authoring toolkits for educational purposes. Therefore, the second requirement for educational AR authoring toolkits is a low level of required programming skills.

Situated learning with AR requires interactivity, leading to careful attention to the context (FitzGerald et al., 2012). Interaction is especially important when students work together in the immersive experience: "For an effective interactive and collaborative education, all the students must be able to see the effects of the interaction at the same time" (Li, 2010). Doing so, the third requirement for educational AR authoring toolkits is a high level of possible interaction for end users.

3 METHODS

3.1 Search Process

To provide an extensive literature overview, we followed the Preferred Reporting of Items for Systematic Reviews and Meta-analyses (PRISMA) Statement (Moher et al., 2009). Moher et al. suggest four phases for collating relevant articles for systematic reviews: *Identification*, *Screening*, *Eligibility*, and *Included*. The search process is reported in **Figure 1**. We gathered documents from five literature databases: ACM, DBLP, IEEEExplore, Scopus, and Web of Science. As research objectives 2 and 3 focus on the assessment and selection of suitable AR authoring toolkits in education (not just academic contexts), we extended the literature database search with selected results from a Google search. The search terms were simple and rather broad, in order to cover as many relevant sources as possible: ("Augmented Reality" AND "Authoring Toolkit"). The exact terms were adapted to the respective databases. This review will provide a 20 years overview of AR authoring toolkits and associated research, which is why the years considered were selected as 2000–2021, published in English. In the *Identification* phase in September 2021, 835 articles were gathered from the databases [ACM Digital Library (evaluated and functional only): 774; DBLP: 2; IEEEXplore: 11; Scopus: 20; Web of Science: 12 and rest from Google Scholar].

3.2 Study Selection

During the *Screening* phase, studies that are not relevant for this review were removed according to general inclusion and exclusion criteria (Moher et al., 2009). Papers not meeting the eligibility criteria were screened out depending on the time, language, type of article, and type of method used (according to the abstracts). The inclusion and exclusion criteria are shown in **Table 1**. A review of the abstracts revealed various articles that were irrelevant, particularly those that did not present, use or evaluate AR authoring toolkits. 80 articles were assessed in the *Screening* phase. After removing 9 duplicates, the full texts of 71 articles were reviewed during the *Eligibility* phase. Here, another 27 articles were excluded as they failed to meet the requirements. 43 articles were included in the meta analysis. The Procedure of search and selection is represented in **Figure 1**.

3.3 Limitations of the Search

Regarding the limitations of this analysis, it is important to consider that 1) the search term was limited to ("Augmented Reality" AND "Authoring Toolkit") in comparison with existing reviews utilising ("Mixed Reality" AND "Authoring Toolkit") 2) not all authoring toolkits are reported in scientific literature. To address this issue, we also included toolkits without explicit literature in the analysis (e.g. those mentioned in another paper or found in the additional Google search). Also, 3) not all toolkits were accessible, either because the projects were discontinued or because they were not free. While discontinued projects are not interesting for educators anyway, this review neglects fee-based toolkits, as it was not possible to collect all necessary data for the classification of these toolkits. 3) For the published evaluations, two potential publication biases have to be kept in mind: Non-significant results might not get published (or are more likely to get rejected by journals/conferences) and project-intern evaluations might only be published if they report positive results.

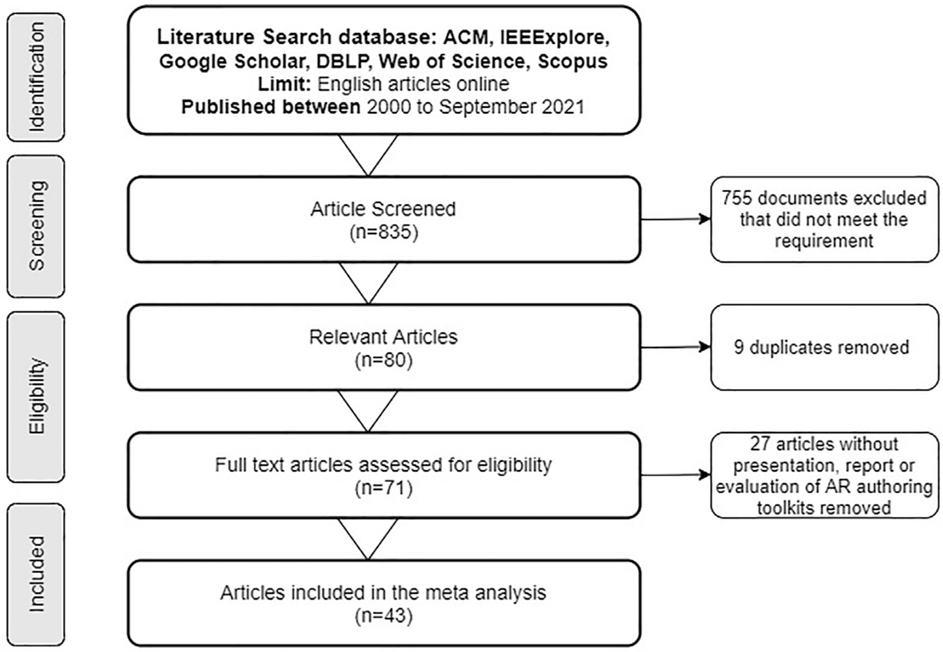

FIGURE 1 | Search process.

TABLE 1 | Inclusion and exclusion criteria.

Criterion	***Inclusion***	***Exclusion***
Time	2000 to 2021	studies before 2000
Language	English	other languages
Type of Article	peer-reviewed research in conference proceedings or journals	other types of documents
Type of Method	studies presenting, using, or evaluating Authoring Toolkits for AR	theoretical articles on AR in general

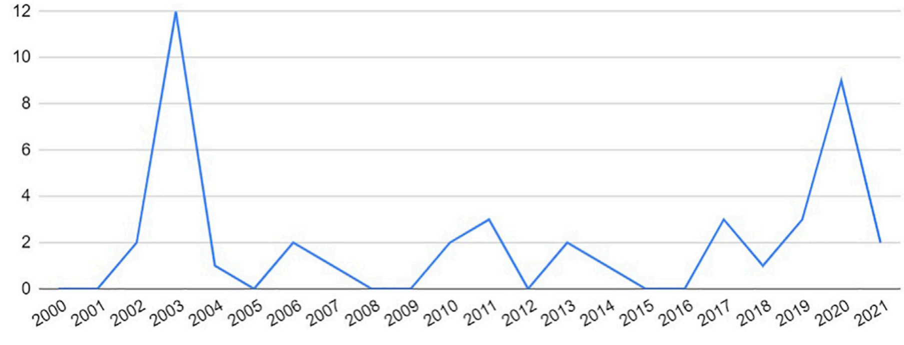

FIGURE 2 | Publication years of the selected articles.

4 RESULTS

Our final corpus contains 43 publications (the included and excluded references for this analysis are shown in **Supplementary Appendix S1A**). In this section, we describe the article characteristics, the reported AR authoring toolkits and existing evaluations on these toolkits. We categorize the toolkits according to their required level of programming skills and provided level of interactivity.

4.1 Article Characteristics

When analyzing the 43 articles regarding their years of publication, it becomes apparent that there is no clear rise or fall regarding the publication count on authoring toolkits for AR.

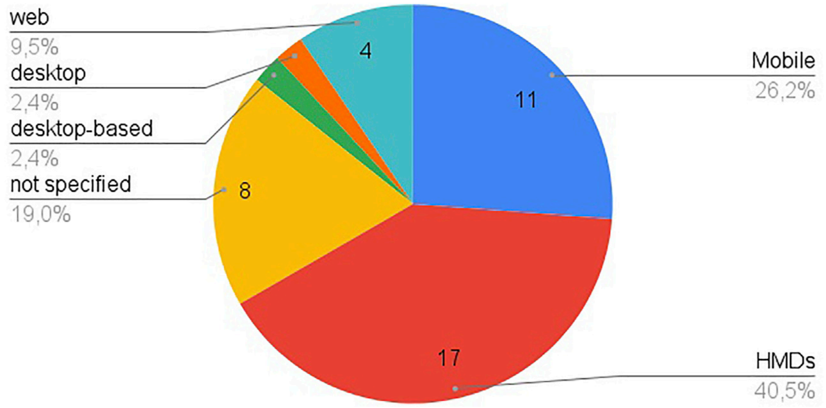

FIGURE 3 | Focused devices in the selected articles.

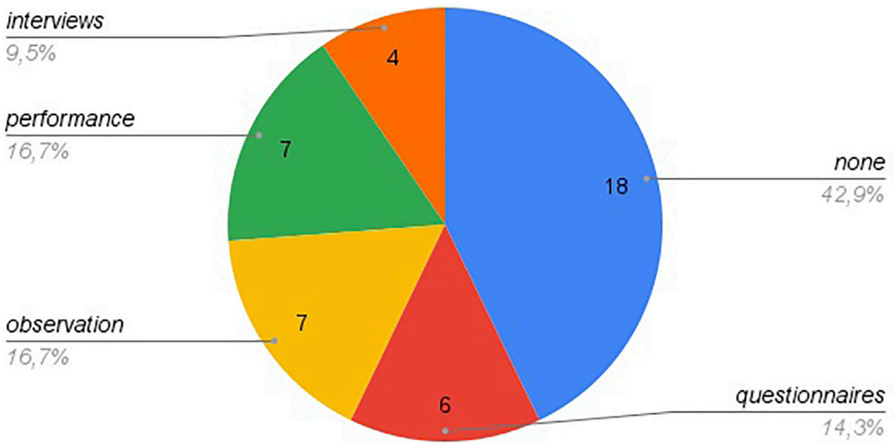

FIGURE 4 | Reported evaluation methods for AR authoring toolkits.

There was an extensive amount of publications in 2003 (due to the IEEE International Augmented Reality Toolkit Workshop in 2003 and the open-source release of ARToolKit in 2001) and a recent increase in 2020 (see **Figure 2**). Most of the papers (90.9%) focus on AR in particular, 9.1% have a mixed focus including e.g. Virtual Reality.

Figure 3 shows the distribution of devices focused on in the articles. Most of the articles focus on Head Mounted Displays (HMDs). Many documents do not specify the devices used, often because the toolkit supports different technologies. A small number of papers focus specifically on mobile phones or tablets and only one paper focuses on building a desktop-based application.

Regarding the toolkits' evaluation, more than half of the papers (17) do not report any evaluation methods (see **Figure 4**). Five papers reported software performance analyses (e.g. framerates). Less than a third of the papers conducted user studies. The few papers which conducted user studies reported the use of observations (four papers), interviews (four papers), and questionnaires (three papers).

4.2 Toolkits Characteristics

21 AR authoring toolkits were directly reported in the papers. Through a backtracking search (using a "snowballing approach" by scanning the references cited in the articles) and an additional Google web search, 48 additional toolkits could be identified. Of this total of 80 AR authoring toolkits (shown in **Supplementary Appendix S1B**) only a bit over a third (36.8%) were openly accessible. One recently published toolkit (Areeka) was added via Google web search as there were no scientific papers focusing on or mentioning this toolkit.

The resulting 26 toolkits were assessed according to the required level of programming skills and interactivity. The selection of these two key defining features was based on current literature on key features for content authoring toolkits (Roberto et al., 2016; Roldán-Álvarez et al., 2016;

TABLE 2 | Accessible AR authoring toolkits and their characteristics.

Toolkit	*Programming Skills*	*Level of Interactivity*	*Source [Date of Access]*
ARToolkit	High	static	ARToolKit (2021)
osgART	High	static	OSGART (2021)
ImageTclAR	medium	dynamic	ImageTcl (2021)
Studierstube	High	dynamic	Studierstube (2021)
DWARF	High	dynamic	Dwarf (2021)
Instant Reality	High	dynamic	InstantReality (2021)
Google Poly	Low	static	GooglePoly (2021)
Unity	High	dynamic	Unity (2021)
Unreal Engine	High	dynamic	Engine (2021)
Google ARCore	high	static	ARCore (2021)
ARKit	high	dynamic	ARKit (2021)
Layar	high	static	Layar (2021)
Vuforia Studio	low	dynamic	Vuforia (2021a)
Blippar	low	dynamic	Blippar (2021)
Wikitude	high	static	Wikitude (2021)
Metaio	low	static	Metaio (2021)
AWE	low	dynamic	AWE (2021)
AR Media Studio	low	dynamic	Inglobe Technologies (2021a)
Spark AR Studio	medium	dynamic	SparkAR (2021)
Snapchat Lens Studio	medium	dynamic	Snap Inc. (2021)
A-Frame	medium	dynamic	A-Frame (2021)
MR Toolkit	high	dynamic	MRToolkit (2021)
DesignAR	low	static	Designar (2021)
MagicBook	low	static	MagicBook (2021)
VEDILS	low	static	Vedils (2021)
Areeka	low	dynamic	Areeka (2021)

TABLE 3 | Academic references to AR Authoring Toolkits, Toolkit Types and citations.

Toolkit	**Academic Source**	**Toolkit Type**	**Citation Count**
ARToolkit	Kato (2007)	static and GUI-based	34
osgART	Looser et al. (2006)	static and GUI-based	102
ImageTclAR	Owen et al. (2003)	interactive and semi-coded	41
Studierstube	Schmalstieg et al. (2002)	interactive and coded	622
DWARF	Bauer et al. (2001)	interactive and coded	310
Balcisoy	Balcisoy et al. (2000)	interactive and coded	61
iaTAR	Lee et al. (2004)	static and coded	223
K-MART	Choi et al. (2010)	static and coded	14
Google Poly	Crawford et al. (2020)	interactive and coded	0
Unity	Kim et al. (2014)	interactive and coded	110
ARScratch	Radu and MacIntyre (2009)	interactive and GUI-based	51
Unreal	Engine Sanders (2016)	static and GUI-based	49
Google ARCore	Lanham (2018)	interactive and coded	33
ARKit	Wang (2018)	interactive and coded	5
Layar	Liao and Humphreys (2015)	static and GUI-based	111
Vuforia Studio	Simonetti Ibanez (2013)	interactive and GUI-based	44
BuildAR	Looser (2010)	interactive and GUI-based	1
Spark AR Studio	Spark (2019)	interactive and semi-coded	4
PoseMMR	Pan and Mitchell (2020b)	static and GUI-based	3
Tiles	Poupyrev et al. (2001)	interactive and semi-coded	111
HoloBuilder	Speicher et al. (2015)	interactive and semi-coded	11
MR Toolkit	Dias et al. (2003b)	interactive and coded	16
DesignAR	Reipschläger and Dachselt (2019)	static and coded	28
MagicBook	Billinghurst et al. (2001)	static and coded	645
VEDILS	Mota et al. (2016)	static and coded	24
Areeka	Buchner and Jeghiazaryan (2020)	interactive and GUI-based	3

Shibolet et al., 2018; Krauß et al., 2021) and usability factors in authoring tools (Murray, 2004; Dağ et al., 2014), that denotes:

1. The required level of programming skills has been defined as follows, based on the existing classification of programming skills required to assess the complexity of

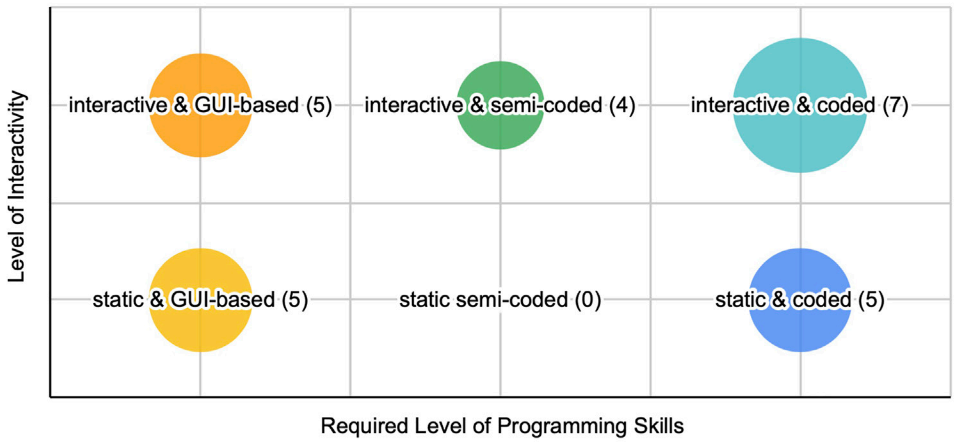

FIGURE 5 | Required programming skills and provided interaction possibilities.

TABLE 4 | Analysis of authoring tools according to affordability (cost), device compatibility, collaboration capacity.

Toolkit	*Affordability* **Free/Commercial Licence**	*Device Compatibility (Web, HMDs, Desktop PC, Smartphones)*	*Collaboration Capacity (Yes/NO)*
ARToolKit (2021)	Free	Smartphone, Desktop	No
OSGART (2021)	Free	Smartphone, Desktop	No
ImageTcl (2021)	Free	Desktop	No
Studierstube (2021)	Free	HMDs	Yes
Dwarf (2021)	Free	HMDs	No
InstantReality (2021)	Free	Desktop, Smartphone	No
GooglePoly (2021)	Free	Web	No
Layar (2021)	Commercial	Smartphone	No
Vuforia (2021a)	Free/Commercial	Web, Smartphone, Desktop	No
Blippar (2021)	Free	Smartphone, Web	No
Wikitude (2021)	Commercial	Web, Smartphone, Desktop	Yes
Metaio (2021)	Free	Web, Smartphone, Desktop	No
AWE (2021)	Free	Web	No
Inglobe Technologies (2021b)	Free/Commercial	Smartphone	No
SparkAR (2021)	Free	Smartphone	No
Snap Inc. (2021)	Free	Smartphone	No
A-Frame (2021)	Free	Web, Smartphone, Desktop	No
MRToolkit (2021)	Free	Web, Smartphone, Desktop	No
Designar (2021)	Free/Commercial	Mobile Web	No
MagicBook (2021)	Free	HMDs	Yes
Vedils (2021)	Free	Smartphone	No
Areeka (2021)	Free/Commercial	Web	No
StoryCreatAR (2021)	Free	HMDs	Yes
Ediphy (2020)	Free	Web	No
Kim et al. (2020)	Free	Smartphone	No
AuthorAR (2013)	Free	Desktop PC	No
ARgent (2020)	Free	Web	No
AugmentedBook (2019)	Free	Smartphone	No
MAGIS (2019)	Free	Smartphone	No
FI-AR (2019)	Free	Web	Yes
BlocklyXR (2021)	Free	Web	Yes

authoring tool for Intelligent Tutoring Systems (Murray, 2016);

- High: no application development possible without programming knowledge, either a coding library or a software framework),
- Medium (application development without coding possible via GUI, additional functionality needs programming),
- Low (application development without the need of programming knowledge, completely GUI-based)

2. In terms of the level of interactivity, which is linked with the creation of static and dynamic content: static (experiences without any interaction, e.g. 3D-models or animations on markers) or dynamic (user-interaction possible). level of

interactivity: static (experiences without any interaction, e.g. 3D-models or animations on markers) or dynamic (user-interaction possible).

Table 2 and **3** show all 26 toolkits, characterized by their level of required programming skills and their level of interactivity. This assessment was conducted by two independent raters, leading to a perfect agreement for the required programming knowledge ($\kappa = 1$) and an almost perfect agreement for the level of interactivity ($\kappa = 0.84$).

When localizing these openly accessible authoring toolkits in a matrix with the two dimensions level of interactivity and required level of programming skills (see **Figure 5**), it becomes clear that most of the toolkits (61.5%) need some sort of coding skills. Only ten of the frameworks are completely GUI-based and do not require prior programming knowledge. Of these frameworks, only five toolkits have the capabilities to create interactive experiences. Affordability, compatibility and collaboration capacity of the toolkits is listed in **Table 4**.

4.3 Toolkits Suitable for Teachers

This section focuses on the five toolkits that do not require prior programming knowledge while still providing the capabilities to create interactive AR experiences in depth. These AR toolkits can be used by teachers to create immersive AR applications for the everyday classroom (or its digital equivalent). The five identified AR authoring toolkits are: Vuforia Studio, Blippar, AWE, AR Media Studio, and Areeka.

Vuforia Studio can transform existing CAD and IoT data into detailed AR experiences. It is designed to provide critical information to front-line workers with animated sequences, for example for intuitive assembly, inspection, service, and operating instructions. Vuforia Studio can efficiently integrate sensor and contextualized IoT data from the ThingWorx platform and from enterprise system data in order to create single viewer applications on mobile devices or on professional headsets such as the Realwear or the Hololens series. Some of Vuforia's strengths comprise fast target identification, precise digital overlays and the placement of 3D virtual products into real-world environments (Vuforia, 2021b).

BlippAR's toolkit Blippbuilder provides an extensive library of 3D models that can be used for AR experiences, but users can upload 3D models on their own as well. Users can add textures and colors to the models. Blippbuilder supports multiple scenes in an AR experience and provides possibilities to animate the 3D-models through movement, rotation, scaling, and fading. Also, users can add videos (e.g., greenscreen videos or livestreams from YouTube) to the AR experience. "Call to Action" events in the AR experience can lead the user directly to a website, an online shop, or to a calendar invite (Blippbuilder, 2021).

AWE is a web-based platform providing AR experiences through smartphones', tablets', computers', or headsets' web browsers. Users can add event actions, animations (e.g., for objects and characters), info panels, quizzes, facial and image recognition, location-based content, and time-based content to enable a rich interactivity in their applications. Five standard scene types are Image AR (using natural feature tracking), Spatial AR (with World Tracking), Face AR (face recognition and augmentation), 360-degree Virtual Reality, and GPS AR (location-based experiences). AWE also provides analytical insides into the usage of the developed experiences (AWE, 2021).

AR Media Studio is a web Authoring Tool used to create, manage and distribute Mixed Reality projects. Virtual scenes can be created as planar projects (on top of a blueprint or poster), as spatial projects (anchored to a specific point in the environment), or as a geo-located project (based on longitude and latitude coordinates). AR Media Studio supports static and animated 3D models, 2D and 360-degree images/videos, audio clips, and HTML5 documents (e.g., apps and mini games). Objects can be animated through moving, scaling, rotating, and rigging. The toolkit also allows collaborative projects (Inglobe Technologies, 2021b).

Areeka is a drag and drop builder that can be used as a WebAR online toolkit. The Image Tracking feature involves the automatic recognition of images captured by the camera. Graphical objects such as 3D objects are superimposed upon them. With the Ground Tracking feature, the device's camera recognizes points that are visible in the real environment and combines them with the AR elements. The forthcoming location tracking feature allows the detection of the user's precise position using GPS coordinates. As a result, the AR experience can be tailored to a specific area. Another forthcoming feature is the object tracking function involving the real-time tracking of objects as they move across frames within a real environment while the augmented content keeps focused on a specific object (Areeka, 2021).

While these five tools were identified as suitable AR authoring toolkits for creating simple educational Mixed Reality experiences according to their ease of use and their provided interactivity, none of the tools were evaluated or developed using an evidence-based, scientific approach (at least not within the literature gathered by the authors, which should have covered relevant articles based on the related search terms).

5 DISCUSSION

5.1 Research Landscape

Regarding RQ1 (*What is the current state of the research on AR authoring toolkits?*), This paper explored a rather divergent scientific landscape: There was no constant rise in research interest but rather several peaks led by new innovations in either hardware or software. For example, the peak in 2003 can be explained by the publication of the ARToolkit framework. The peak in 2011 could be driven by the release of the first iPad in 2010 and/or by the general rise of interest in immersive technologies in 2010 through the release of the Oculus Rift consumer version. The latest peak of 2020 could be explained through the release of the Hololens 2 in 2019 and other MR HMDs.

Almost half of the research papers on AR authoring toolkits report the use of HMDs, which contradicts the broad use of smartphones and tablets for AR in Education (FitzGerald et al., 2012). It must be noted that over a third of the papers did not specify the devices for using the toolkits. While this could simply mean that the toolkits are not hardware-specific, research shows that user experience and learning performance differ strongly between technologies, based on their individual characteristics (Author, 20xxa, blinded for review), leading to the need of an evidence-based evaluation of AR authoring toolkits.

This also becomes clear when taking a closer look at the empirical aspect of the assessed articles. Over half of the papers did not conduct any empirical research and not even a third conducted user studies. While performance analyses are an important part of system evaluations, educational tools need to be evaluated by the people who use them: teachers. This might be one of the most important takeaways of this review: There is an urgent lack of research-informed design of AR authoring toolkits for education. Developers and educators need to work closely together in order to meet the requirements of developing AR experiences for the everyday classroom.

5.2 Characteristics of AR Authoring Toolkits

A focus on the toolkits' accessibility, their required level of programming skills, and their developmental capabilities (RQ2) shows that over half of the tools reported in the scientific papers are not accessible. They were discontinued or not made publicly available. This raises questions about the reliability of such tools for educational development. Having to change to a different Authoring Toolkit after a year or two is tedious and could keep educators putting in the effort of learning how to use such toolkits.

Most of the currently accessible authoring toolkits enable interactive experiences, but, on the other hand, most of the accessible toolkits also require at least some sort of programming knowledge for content creation. There are some GUI-based toolkits that do not require any coding skills; half of them allow the development of interactive experiences. As educational AR experiences require interactivity in order to enable experience-based and experimental learning (FitzGerald et al., 2012; Huang et al., 2016) and as only a few teachers have any computer science background, the characteristics *dynamic interactions* and *GUI-based programming* were selected as desirable features of AR authoring toolkits for educators.

5.3 AR Authoring Toolkits for Educators

Five toolkits met the identified features of AR authoring toolkits for educational purposes. While each of the toolkits offer slightly different possibilities and functions, Vuforia Studio, BlippAR, AWE, AR Media Studio, and Areeka can all help facilitate the development process of educational AR experiences. Still, usability studies with educators regarding the development process are still lacking for all of these toolkits.

When improving these existing AR authoring toolkits or creating new toolkits, this research gap needs to be addressed: An evidence-based and research-informed development and iterative improvement process is not only desirable but strongly needed. Doing so, educators can become part of the design process, which can foster the integration of Augmented Reality in education.

Bloom's Taxonomy provides guidance for creating interactive content generating tools. The objectives of this model are cognitive, psychomotor and affective domains. There are six categories in the cognitive domain as knowledge, comprehension, application, analysis, synthesis and evaluation as explained in **Figure 6**.

6 LIMITATIONS

This review had a narrow focus on AR authoring toolkits and their value for educators. Thus, the results of this analysis are of special interest to teachers and their requirements but cannot be generalized to other application areas, as different developers have different needs (even though some might be very similar). While the five identified toolkits are suitable for educators without programming knowledge, many educators are in fact willing to learn or already know basic algorithmic components and structures. Being able to program object behaviors can facilitate the process and provide further opportunities supporting the educational objective.

Also, the categories GUI-based, semi-coded, and coded are rather broad. Especially block-based coding environments, as tested in ARScratch (Radu and MacIntyre, 2009), can be easy to learn and could even be used in Computer Science Education classes to create AR applications together with students. A current approach focusing on virtual environments, but also having an "AR Cube" option, is CoSpaces (CoSpaces, 2021). In some cases, such block-based coding environments might be even easier to learn compared to complex GUI-structures.

It has to be noted that many of the toolkits were not accessible and, thus, only a part of the developed Authoring Tools could be assessed. Also, as not all authoring toolkits, especially newer ones, are represented in scientific literature, it is possible that some existing toolkits were missed by this review. Measures to minimize these limitations were taken (e.g. an additional Google web search and a backtracking/ snowballing approach on the toolkits reported in the papers were conducted).

7 IMPLICATIONS FOR THE DESIGN OF AN AUTHORING TOOLKIT WITH AN EDUCATIONAL PURPOSE

AR authoring tools are getting more importance for creating and delivering contents in the classroom setting or virtual learning to replace the traditional classroom settings. The role of authoring tools in education has increased due to rapid adoption of online education. There is a need to increase the competency of authoring frameworks to provide more adaptive, engaging and collaborative experience with better usability for the teachers with no programming skills. The major implications involve the affordances and pedagogical issues attached with the authoring tools.

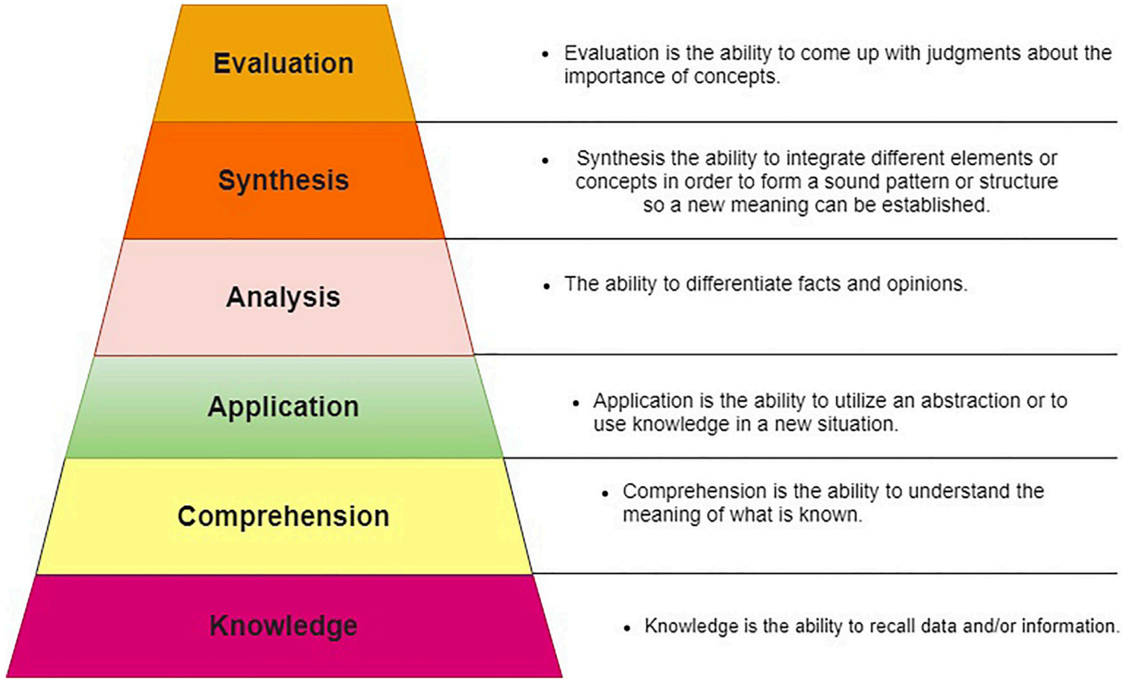

FIGURE 6 | Bloom's Taxonomy with six categories (Anderson and Sosniak, 1994).

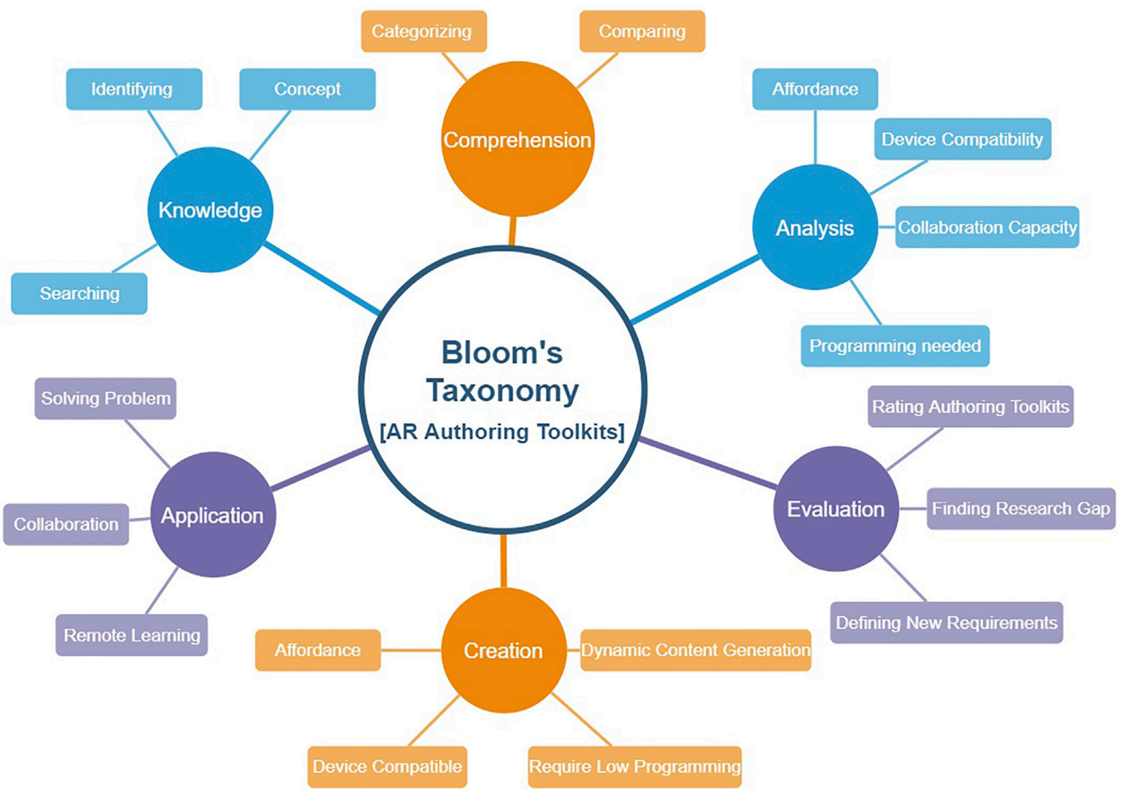

FIGURE 7 | Bloom's Taxonomy; From existing work to future goal of the project.

7.1 Conclusion

This literature review investigated the research landscape and the characteristics of existing AR authoring toolkits with regards to their accessibility, required level of programming skills, and developmental capabilities. We identified suitable toolkits for educators that allow the development of interactive experiences without requiring programming skills.

The research landscape investigated in RQ1 (*What is the current research landscape on AR authoring toolkits?*) is divergent and does not show a constant research interest in AR Authoring Toolkits. HMDs are the dominant technology assessed in the articles, followed by mobile phones/tablets. More than half of the articles did not report any empirical evidence supporting their research.

In RQ2 (*What are the characteristics of these authoring toolkits regarding their accessibility, required level of programming skills, and developmental capabilities?*), the characteristics of these Authoring Toolkits regarding their accessibility, required level of programming skills, and developmental capabilities were investigated: Over half of the AR Authoring Toolkits reported in the literature were not accessible or discontinued. Most of the accessible toolkits can be used for developing interactive AR experiences. Over half of the toolkits required at least some sort of programming knowledge.

The investigation of RQ3 (*Which of these authoring toolkits are suitable for teachers to create educational AR experiences for the classroom?*) led to five toolkits meeting the needs of teachers in designing educational AR experiences. These openly accessible toolkits (Vuforia Studio, BlippAR, AWE, AR Media Studio, and Areeka) can help educators in creating interactive educational AR applications to support teaching and learning in the everyday classroom without the requirement of previous programming knowledge.

These findings support previous research efforts (e.g., Freitas et al. (2020); Nebeling and Speicher (2018)) that analyzed AR authoring toolkits in general by not only adding more recent tools to the landscape, but especially by taking an educational perspective on existing AR Authoring Toolkits by analyzing these tools with regards to teachers' needs when developing AR experiences for the everyday classroom.

This review identified three main research gaps that should be addressed in future design and evaluation of AR authoring toolkits:

- AR authoring toolkits need to be evaluated within the context of the hardware that is being used for visualizing the immersive experiences.
- Empirical research projects, especially user studies with teachers, are needed to develop and improve AR authoring toolkits for education.
- Low required programming skills and dynamic, interactive experiences are desirable features for AR authoring toolkits used by educators, but existing options are still scarce.

As stated before, the main takeaway of this paper is the strong need for empirical data regarding the target group of such toolkits when using them for educational purposes: Teachers' use and development experiences with these tools are crucial for their improvement. As AR has the potential to function as a powerful educational tool in remote education (Li, 2010) and assessment (Wang et al., 2010), further developments and improvements are strongly needed. But, of course, focusing students as the end-users of the immersive experiences is just as important. Thus, interdisciplinary collaborations between software developers, researchers from informatics, human-computer-interaction and educational sciences, educators, and students are necessary for a sound long-term integration of Augmented Reality in the classroom.

7.2 Future Work

Following **Figures 6**, **7** of expanded Bloom's Taxonomy, the ARETE H2020 project (Arete, 2021b) aims to change the landscape of AR content creation, via AR authoring toolkits, demonstrated in applications for education and training through the pilot studies. Augmented Reality content authoring uses end-user friendly *in-situ* authoring (Arete, 2021a) based on the authoring and re-enactment toolkit WEKIT HoloLens smart glasses application (WEKIT, 2021) (now: MirageXR Community Edition, Open Source). MirageXR (Mirage XR, 2021) has been utilized, where authors place world anchors into the environment and attach one or more augmentations to it setting triggers for workflow-like learning activity execution. Besides standard augmentations such as text, video, image or audio, this includes additional instructional design elements with sensor input and 3D models. For example, it is possible to capture movement, gaze focus, teacher voice, to create an automated recording of a teacher/instructional designer demonstrating how to do something, or to explain with a think-aloud protocol what learners have to pay attention to. Content authors sequence a learning activity (Augmented Scene) into a series of action steps to provide the learning material required for developing competence in a specific learning activity. The main objective of the ARETE authoring toolkit is to address the current research gaps in the 3D authoring tools for educators and contribute to existing standards. While seeking to educate consumers, governments and industry about AR's potential, the ARETE consortium aims to further advance and evaluate the deployment of AR technology, through a number of pilot interventions in Europe during the academic year 2021/2022.

Although the reported evaluation methods within this work include only interviews, performance measures, observations and questionnaires, future work will include research on the different metrics of XR authoring toolkits usability (UX design, user capacity, educational cognitive tasks' pathway, flexibility, accessibility, effectiveness, efficiency, satisfaction, impact on learnability, data analytics provision). This will involve experts, users and automated usability testing.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frvir.2022.798032/full#supplementary-material

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