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Authoring Tools for Virtual Reality Experiences: A Systematic Review

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Abstract Virtual reality (VR) is used in different application fields like health, tourism, or training. Most VR applications for these fields have been built from the ground up without any authoring tool to help the process. This systematic review surveys the existing literature on authoring tools for immersive content and critically analyzes its features and how they are evaluated. It proposes a research agenda with key contribution opportunities for the field.

An analysis of the 29 studies that met the eligibility criteria revealed that four records did not present any evaluation regarding the authoring tools' evaluation, and only five records used specialized users to evaluate their authoring tools; all the others used non-specialized users. The most evaluated metrics were usability, effectiveness, efficiency, and satisfaction. The data collected to evaluate the metrics consisted mainly of Likert scales and reported mean opinion score (MOS). However, few records used well-established questionnaires to evaluate those metrics like System Usability Scale, Post-Study System Usability Questionnaire, After-Scenario Questionnaire and Igroup Presence Questionnaire. Additionally, five of the analyzed records included stimuli other than audiovisual. More research is recommended about the usage of ontologies in authoring tools to comprehend the full potential of its usage since none of them had ontologies.

Keywords Systematic Review · Virtual Reality · Immersive Experiences · Authoring tools

1 Introduction

Virtual reality (VR) popularity has been increasing over the years and its usage. This technology's primary focus is to transport the user to new environments and develop the "sense of being there", widely known in the literature as presence [48, 44]. This feeling is created by having coherent perceptual feedback corresponding

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to users' actions so that they think that they are an actor in the world they see [44]. Having such a feeling, users behave as they would in the real world when exposed to the same circumstances. Presence can also be affected by Immersion, which describes the system's technical ability to surround all users' senses [44]. Witmer and Singer [51] also defined Immersion as a psychological state characterized by perceiving oneself to be enveloped by, included in, and to interact with the virtual environment, which provides a continuous stream of stimulus experiences.

Because of the popularity and what VR technology allows, it has been used in a wide range of areas such as health [18], tourism [21], training [37] or entertainment [26]. With the increase of applications developed for VR and the need to create more realistic/credible experiences, newer and better applications were developed using multisensory stimuli. This new addition to VR experiences increases the users' presence and, by doing so, increases their overall experience [15, 19, 45]. Literature also states that increasing the number of stimuli presented to the user can increase users' cognitive load if the stimuli are not coherent [2, 4].

Depending on the application areas, these new VR applications can help the market increase profitability by reducing the cost to train operatives while allowing them to train in a safe environment [31]. A significant problem that is a barrier to the adoption and widespread of such VR technologies is that they take much time to develop and require highly specialized professionals [27]. The VR application development must go through various iterations until it reaches a high maturity state and is ready for production. Authoring tools can solve this problem by making new VR content easier, faster, and more efficient. Re-usage of content can also make the content creation process more manageable since it removes the need to develop the same asset every time a new experience is created/edited [41]. Consequently, this decreases the time to create/edit content and reduces the cost.

Kaskalis et al. [23] surveyed the literature searching for authoring tools for educational content retrieving data related to which text, video, audio and image files are supported by each authoring tool, features and graphical user interface. Arndt and Katz [1] also surveyed the literature for visual authoring tools for multimedia content retrieving the same data as Kaskalis et al. [23] survey. A survey was published regarding mobile authoring tools for cultural heritage retrieving authoring tools that serve that purpose [17]. In this survey, the authors briefly described the concep and user interaction design and architectural and technological design.

Despite the literature mentioning authoring tools, there is no knowledge about the technology used on them, how they were evaluated, or even if they have been developed for a specific application field. Furthermore, there is no information if such authoring tools are only being developed to be used traditionally, on a desktop, or if they are being developed to be used using VR technology. VR immersive authoring tools can bring to the table a significant advantage to traditional authoring tools by providing a "What you see is what you get" environment to create content [12, 11], using this, developers/content creators have an intuitive interface allowing them to have real-time feedback on how the content will be presented to the end-user, decreasing the number of iterations and possibly speeding up the time needed to finish the VE.

This systematic review aims to address this gap in the literature and provide a comprehensive overview of the studies that present and develop authoring tools designed for creating immersive VR experiences. Moreover, we consider immersive VR systems that fully immerse the user through headsets [7] and immersive ex-

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periences as experiences that need to be viewed through immersive VR systems. In this comprehensive systematic review, we analyze the main application fields of the authoring tools; the capability of the authoring tools to reuse/import content assets; if it is required specialized knowledge to use the identified authoring tools; what methods and metrics can be used to evaluate such authoring tools. With such systematization of the literature, we critically analyze the current status of this area of knowledge and its main gaps. Furthermore, we propose a research agenda to guide future research work regarding authoring tools for immersive VR to pave the evolution of this research field. Additionally, a significant contribution of this work is a searchable database to enable readers to quickly sort through the analyzed literature, promoting knowledge sharing in the field. Moreover, the results can help design, create, and evaluate new authoring tools by showing the features and limitations and the most used methods and metrics used to evaluate them.

2 Methodology

This systematic review followed a PRISMA methodology proposed by Moher et al. [36] which guides the development of systematic reviews and meta-analysis. This methodology ensures a transparent and complete reporting of the surveyed topics.

2.1 Eligibility Criteria

Publications were considered eligible for inclusion if they involved developing/evaluating an authoring tool designed to create immersive VR experiences. The inclusion criteria were:

1. The entry title, abstract or keywords had one or more of the terms described on Subsection 2.2;
2. Manually identified entries;
3. The entry is published in a refereed journal or conference;
4. The entry is written in English.

Moreover, publications were excluded using the following exclusion criteria:

1. Is a duplicate entry;
2. The entry is written in a language other than English;
3. Entry text is not available;
4. Entry is one of the following: technical report, abstract, conference proceeding, conference review, editor's note, call for papers, literature review;
5. Entry is a theoretical work (e.g., information system proposal, literature review, poster);
6. Entry is out-of-scope (does not consider authoring tools or does not create VR experiences);
7. Entry does not consider VR;
8. Entry authoring tool only allows editing rather than creating immersive VR experiences;
9. The content created by the authoring tool is not immersive.

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2.2 Search Strategy

All available entries were retrieved through electronic searches by conducting extensive searches on indexing databases. The databases used were Web of Science: Web of Science Core Collection (Thompson Reuters), Elsevier Scopus, and ACM Digital Library. The first search was performed on 10^{th} October 2021 and was performed using the query equivalent to the one shown below for all the aforementioned indexed databases:

> Title/Abstract/Keyword(("creator" OR edit* OR "builder" OR "maker" OR "authoring") AND ("immersive" OR "cave" OR "hmd" OR "head mount display" OR "head mounted display" OR "head-mount display" OR "head-mounted display" OR "headset"))

Please note that, for this review, we only considered studies with ten (10) years or less from the time of writing of this review.

2.3 Study Selection

After having all entries that match the search query defined above (Section 2.2), eligibility assessment and data extraction were performed independently in a conventional, unblinded standardized manner by a total of three reviewers (GG, HH, PM). Two reviewers reviewed each entry to determine its eligibility, taking title, abstract, and keywords into account. The decision was made if the two reviewers reached a consensus (accept or reject). The entry was conditionally accepted for full-text analysis if no consensus was found.

2.4 Data Collection Process

All entries selected for full-text assessment were reviewed, and the data collection process was conducted using predefined and piloted forms. The retrieved variables are:

- Type of authoring tool - This variable can be classified as two options: plugin or standalone. A plugin is software developed to work over other software to facilitate processes. On the other hand, a standalone is a software that works without any other software and is designed specifically for a purpose;
- Type of content created - This variable can be divided into three categories: Video, 360 Video or VE. Video refers to a simple 2D video, while 360 video refers to a video where the user is not locked to a single view and can look around to explore other sights, and VE is a complete VE where everything that the user sees is a 3d model;
- Area of application - Refers to the field where the authoring tool was developed and meant to be applied for, and this was defined based on the International Standard Classification of Occupations 2008 (ISCO-08), a system to classify and aggregate occupational information [39];

- Experienced Users - This variable can be classified as two options: None or Specialized Users. None means that the user has no knowledge or does not work with any software that executes the same process performed by the authoring tool. On the other hand, Specialized User means that the user has the knowledge or works with software that executes the same process performed by the authoring tool;
- Importation or reuse of content - This was retrieved directly from the analyzed records if they stated that the authoring tool supports (marked as "Yes") or not (marked as "No") the reuse or importation of assets. If they do not say anything regarding this topic, nothing was retrieved and appeared in the results of this survey as "-";
- Immersive Tool - Variable that shows if the authoring tool was immersive or not;
- Stimuli used - Variable that lists the stimuli used other than visual and audio stimuli;
- Advantages - Advantages of authoring tool reported by authors;
- Limitations - Limitations of the authoring tool reported by authors;
- Evaluation Metrics - Metrics used to evaluate the authoring tools;
- Evaluation Methods - Methods used to evaluate the authoring tools;

2.5 Quantitative Analysis of the Entries

After retrieving all the data mentioned in Subsection 2.4), a quantitative analysis was conducted. The quantitative analysis comprises a graphical representation of the most used terms in the analyzed paper titles (word cloud). To generate a more valuable word cloud and decrease the number of outlier terms, some rules were applied such as: Remove terms that are not important (e.g., pronouns), merge terms that only make sense together (terms like "virtual" and "reality" were merged into "Virtual Reality"), merge singular and plural terms (terms like "Experience" and "Experiences" were merged and only appear as "Experiences") and group terms that have the same meaning (e.g., "head-mounted display", "HMD" and "headset" were merged into "HMD").

2.6 Qualitative Assessment of the Entries

A scoring system was adopted to assess the quality of accepted papers for full-text analysis. This system was inspired by the quality assessment approach proposed by Connolly et al. [13], Feng et al. [16] and Melo et al. [33]. The scoring system was designed so that the value 1 refers to the lower score and, depending on the question, the values 2 or 3 are the higher score (defined below). Similarly to study selection, two reviewers scored each study on each of the questions, and if a consensus was reached, the score for that study was closed. On the other hand, if the reviewers did not reach a consensus, a third reviewer would moderate the score and provide a consensus. To be considered a high-quality paper, it has to have more than 7 points when adding the scores of all quality assessment questions, and this cutline was decided by calculating the mean total score of all papers (the mean score was 6.90). The following assessment questions were considered:

- **QA1** - Was the paper published in a journal or a conference? If the paper was published in a conference as a short paper, it received a score of 1 point; if the paper was published in a conference as a full-paper, it was given 2 points; and if it was published in a journal, it was given 3 points.
- **QA2** - Was the sample size used in the evaluation process enough, taking into account the number of independent variables? For example, if the number of participants was fewer than the recommended or the authoring tool was not evaluated, it received a score of 1 point; if the number of participants was acceptable, it was given 2 points; and if the number of participants was above the recommended, it was given 3 points.
- **QA3** - Was there any limitations reported? If there were substantial limitations reported on the paper, it received a score of 1 point; if there were some limitations reported, it was given 2 points; and if there were no limitations reported, it was given 3 points.
- **QA4** - Was there any stimuli other than visual and smell used by the authoring tool? If the paper did not report that the authoring tool could allow the usage of other stimuli, it received a score of 1 point; on the other hand, if the paper reported that the authoring tool could allow the usage of other stimuli, it was given a score of 2 points.

3 Results

The process of retrieving the papers that matched the query above mentioned in Section 2.2 in the identified databases resulted in a total of 1478 records. From the 1478 records, 285 were identified as duplicates and consequently removed, resulting in a total of 1193 unique records. The title and abstracts of the unique records were analyzed, considering the previously defined eligibility criteria (Section 2.1). From those, 1014 records were excluded using the exclusion criteria. This resulted in 179 records being eligible for full-text analysis. From those 179 records, 150 were excluded based on the previously defined exclusion criteria, resulting in 29 records included in the qualitative synthesis. Please refer to Figure 1 for a detailed overview of the study selection.

3.1 Qualitative Analysis of the Extracted Data

Since the records' qualitative analysis is extensive, the research team opted to group the extracted data by research questions. This allows a more accessible reading and a better understanding of each research question.

3.1.1 Context of the Authoring Tools

Table 1 shows how the authoring tools developed are distributed in type, content, application field (taking into account the ISCO-08),importation or reuse of content, user knowledge and if the editor is an immersive authoring tool. This is further discussed in the 4.1, 4.2, and 4.3 subsections.

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Table 1 Context details of all the identified studies.

Study	Year	Type	Content	Application Field	Knowledge level	Import or Reuse Content	Immersive Tool
Shah et al. [43]	2020	Standalone	360 Video	General Purpose	None	-	Yes
Shah and Lee [42]	2019	Standalone	360 Video	General Purpose	None	Yes	Yes
Coelho et al. [12]	2019	Standalone	360 Video	General Purpose	None	Yes	Yes
Puget et al. [40]	2019	Plugin	360 Video	Graphic and Multimedia Designers	-	-	Yes
Horst et al. [22]	2019	Standalone	360 Video	General Purpose	None	-	Yes
Coelho et al. [11]	2019	Standalone	360 Video	General Purpose	None	Yes	Yes
Blonna et al. [5]	2018	Plugin	Virtual Environment	General Purpose	None	-	Yes
Nguyen et al. [38]	2017	Standalone	360 Video	General Purpose	Specialized User	Yes	Yes
Leon et al. [29]	2016	Standalone	Virtual Environment	General Purpose	None	Yes	Yes
Zarraonandia et al. [52]	2016	Standalone	Virtual Environment	General Purpose	None	-	Yes
Wang and Lindeman [49]	2014	Standalone	Virtual Environment	General Purpose	None	-	Yes
Zhao and Ma [54]	2020	Plugin	360 Video	General Purpose	None	No	No
Bassbouss et al. [3]	2019	Standalone	360 Video	General Purpose	None	-	No
Kim [25]	2019	Standalone	Virtual Environment	General Purpose	None	-	No
Danieau et al. [14]	2018	Plugin	Virtual Environment	Graphic and Multimedia Designers	Specialized User	-	No
Mo et al. [35]	2018	Plugin	Virtual Environment	Construction Supervisors	-	-	No
Coelho et al. [10]	2018	Standalone	360 Video	General Purpose	None	No	No
Chu et al. [9]	2017	Standalone	360 Video	General Purpose	None	-	No
Gai et al. [20]	2017	Standalone	Virtual Environment	General Purpose	None	-	No
Lee et al. [28]	2017	Standalone	Virtual Environment	General Purpose	None	-	No
Meira et al. [32]	2016	Standalone	360 Video	General Purpose	None	No	No
Khundam [24]	2020	Plugin	Virtual Environment	Gallery, Museum and Library Technicians	None	-	No
Cassola et al. [8]	2021	Standalone	Virtual Environment	Mechanical Engineering Technicians	-	Yes	Yes
Zidianakis et al. [55]	2021	Plugin	Virtual Environment	Gallery, Museum and Library Technicians	Specialized User	-	No
Zhang and Oney [53]	2020	Standalone	Virtual Environment	General Purpose	None	-	Yes
Zikas et al. [56]	2020	Standalone	Virtual Environment	General Purpose	Specialized User	-	Yes
Torres et al. [46]	2020	Standalone	360 Video	General Purpose	None	-	No
Mendes et al. [34]	2020	Standalone	360 Video	General Purpose	-	-	Yes
Wilcocks et al. [50]	2020	Plugin	Virtual Environment	Medical Doctors	Specialized User	Yes	No

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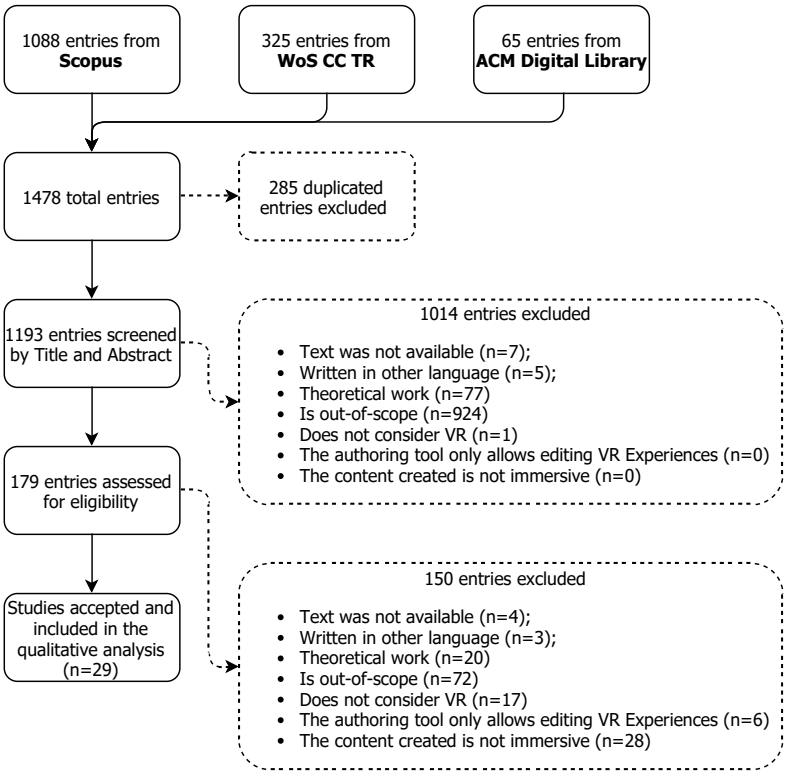

Fig. 1 Flow diagram with inclusion and exclusion criteria.

3.1.2 Evaluation Used on Authoring Tools

Table 2 shows what methods of evaluation and what variables were used to evaluate the developed authoring tools. This is further discussed in the 4.4 subsection. Here will be defined the acronyms used in the table: MOS - Mean Opinion Score; SUS - System Usability Scale; ASQ - After-Scenario Questionnaire; IPQp - Portuguese Igroup Presence Questionnaire; SSQ - Simulator Sickness Questionnaire; FPS - Frames per Second, EDA - Electrodermal Activity; HR - Heart Rate; RD - Respiratory Depth; PSSUQ - Post-Study System Usability Questionnaire; GEQ - Game Experience Questionnaire; UEQ - User Experience Questionnaire.

3.1.3 Stimuli Used by Authoring Tools

Table 3 shows the stimuli considered by the authoring tools when creating immersive experiences (beyond audiovisual). Note that the term "None" means that no other stimuli were presented besides visual and sound. This is further discussed in the 4.5 subsection.

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Table 2 Variables and methods used to evaluate each authoring tool.

Study	Variables	Methods
Shah et al. [43]	Usability Efficiency Satisfaction	MOS (Likert scale 1-5)
Shah and Lee [42]	Usability Efficiency Satisfaction	MOS (Likert scale 1-5)
Coelho et al. [12]	Usability Efficiency Effectiveness Satisfaction	SUS ASQ
Puget et al. [40]	-	-
Horst et al. [22]	Usability Satisfaction	MOS (Likert scale 0-6)
Coelho et al. [11]	Usability Efficiency Effectiveness Satisfaction Presence	SUS ASQ IPQp
Blonna et al. [5]	Satisfaction	MOS (Likert scale 1-5)
Nguyen et al. [38]	Usability Cybersickness	MOS (Likert scale 1-5) Post-Exposure SSQ
Leon et al. [29]	Effectiveness	Observation (Time)
Zarraonandia et al. [52]	Usability Satisfaction	MOS (Likert scale)
Wang and Lindeman [49]	Usability Satisfaction	MOS (Likert scale 1-6)
Zhao and Ma [54]	Usability Immersiveness	MOS (Likert scale 1-7)
Bassbouss et al. [3]	Effectiveness	Performance
Kim [25]	Effectiveness	Observation (FPS, Polygons, Time)
Danieau et al. [14]	Usability Satisfaction	MOS (Likert scale 0-5)
Mo et al. [35]	-	-
Coelho et al. [10]	Usability Effectiveness Satisfaction	SUS Observation (Help requests)
Chu et al. [9]	Usability Effectiveness	MOS (Likert scale)
Gai et al. [20]	Usability Satisfaction User response	PSSUQ MOS (Likert scale 1-7) Biometric Data (EDA, HR, RD)
Lee et al. [28]	Effectiveness Cybersickness	Observation(FPS, Polygons) SSQ
Meira et al. [32]	Usability	SSQ
Khundam [24]	Interactions	Observation (Number of interactions with objects)
Cassola et al. [8]	-	-
Zidianakis et al. [55]	Usability	MOS (Likert scale 1-5)
Zhang and Oney [53]	Advantages/Disadvantages Usability Learnability	User Reports MOS (Likert scale 1-5)
Zikas et al. [56]	Usability User Experience	Observation (Time, Help Requests) MOS (Likert scale 1-5)
Torres et al. [46]	Usability Game Experience	SUS GEQ
Mendes et al. [34]	-	-
Wilcocks et al. [50]	Usability User Experience User reports	SUS UEQ Open Questions

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Table 3 Stimuli present in the authoring tools.

Study	Stimuli
Shah et al. [43]	None
Shah and Lee [42]	None
Coelho et al. [12]	Haptic, Smell
Puget et al. [40]	None
Horst et al. [22]	None
Coelho et al. [11]	Haptic, Smell
Blonna et al. [5]	None
Nguyen et al. [38]	None
Leon et al. [29]	None
Zarraonandia et al. [52]	None
Wang and Lindeman [49]	None
Zhao and Ma [54]	None
Bassbouss et al. [3]	None
Kim [25]	None
Danieau et al. [14]	Haptic
Mo et al. [35]	None
Coelho et al. [10]	Haptic, Smell
Chu et al. [9]	None
Gai et al. [20]	None
Lee et al. [28]	None
Meira et al. [32]	None
Khundam [24]	Haptic
[8]	None
Zidianakis et al. [55]	None
Zhang and Oney [53]	None
Zikas et al. [56]	None
Torres et al. [46]	None
Mendes et al. [34]	None
Wilcocks et al. [50]	None

3.1.4 Features and Limitations of the Authoring Tools

Table 4 shows all the features and limitations of each authoring tool. All data retrieved was obtained directly from what the authors reported as advantages and limitations. This is further discussed in the 4.6 subsection.

Table 4: Features and limitations of each authoring tool.

Study	Features	Limitations
Shah et al. [43]	Object Recognition; Multiple areas of Interest; Multiple Experiences from a single video;	Object recognition fails when next to edges; The user has to see the same video multiple times;
Shah and Lee [42]	Saves orientation of the content creator;	Only orientation is saved;
Coelho et al. [12]	Creation of multisensory experiences; Real-Time experience visualization; Collaborative;	Only supports 360 Videos;

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Puget et al. [40]	Creation of a 360 video from a VE with 3D content; HMD controls the position of the virtual camera;	Sounds are not recorded;
Horst et al. [22]	Allows labelling of objects in a 360 Video;	Highlighted objects must be static;
Coelho et al. [11]	Creation of multisensory experiences; Real-Time experience visualization; Multiple interaction methodologies;	Only support 360 Videos
Blonna et al. [5]	Creation of a virtual environment inside VR;	Predefined tasks; No collaboration;
Nguyen et al. [38]	Addition of Markers/Labels to a 360 Video;	No advanced timeline; No usage of expressive controllers; Only tested with monoscopic videos;
Leon et al. [29]	Natural interaction; Connects to an asset database;	Only predifined assets were available;
Zarraonandia et al. [52]	Multiple interaction methodologies; Usage of natural interaction methodologies;	Does not use immersive controllers; Does not evaluate Cybersickness;
Wang and Lindeman [49]	Usage of different devices (HMD + Tablet); Synchronization between both devices;	Can not use both devices at the same time;
Zhao and Ma [54]	2D illustrations placed in a 3D VE and turned into a 360 Video; Allows users to animate images;	Predefined images only; Animation effects not satisfactory;
Bassbouss et al. [3]	Advanced timeline editor; Works with multiple devices;	Only supports HTML and WebGL;
Kim [25]	Creates different mazes;	Only creates mazes;
Danieau et al. [14]	Creation of haptic stimulus to be used in a VE; Support for several haptic devices;	Only creates haptic stimulus
Mo et al. [35]	Creation of data-driven scenarios for VR;	The user is only a spectator;
Coelho et al. [10]	Creation of multisensory Experiences; Allows previewing the 360 Video experience in VR; Stimuli timeline visualization;	Does not allow to modify the experience in VR;
Chu et al. [9]	Creation of navigable 360 Videos;	Simple interactions; Can cause cybersickness

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Gai et al. [20]	Creates a maze using markers on the floor;	The maze has to be a square; Needs a real world space;
Lee et al. [28]	Creates different mazes;	Can only generate finite square patterns;
Meira et al. [32]	Allows 360 Video annotation;	Created annotations can be distracting;
Khundam [24]	Creates storytelling experiences to be used in a museum	No support for multi-user experiences
Cassola et al. [8]	Creation of training scenarios using models of real object	The authoring tool is only specific to training scenarios Heavy model loading
Zidianakis et al. [55]	Creation of virtual museums	Framework used limits the number of light sources
Zhang and Oney [53]	Creation of interactive scenarios Uses visual programming	Does not support particle system
Zikas et al. [56]	Creation of training scenarios using visual programming	Interactive components are not intuitive
Torres et al. [46]	Addition of annotations, quizes, images and objects to 360 video	Authoring tool is not immersive
Mendes et al. [34]	Declarative authoring model to support authors in the process of designing and creating 360-degree videos	-
Wilcocks et al. [50]	Creation of Anesthesia Crisis-based scenarios	Authoring tool is specific for anesthesia crisis simulations

3.2 Quality Assessment of Entries

The scoring of the 29 selected records in the full-text analysis revealed an average score of 6.69. Figure 2 shows the histogram with quality scores and data quartiles. We considered records with a score lower than six as low-quality records. Records between 6 and 8 were considered medium-quality, and those with a higher score than eight were considered high-quality. Table 5 shows the records distributed by the quality assessment category. The score for each quality assessment question can be found in Figure 3.

3.3 Quantitative Analysis of Entries

The titles of the 29 records analyzed were retrieved and processed to perform quantitative analysis and a graphical representation, in the form of a word cloud (shown in Figure 4). The larger the term's visual representation, the more frequently they appear.

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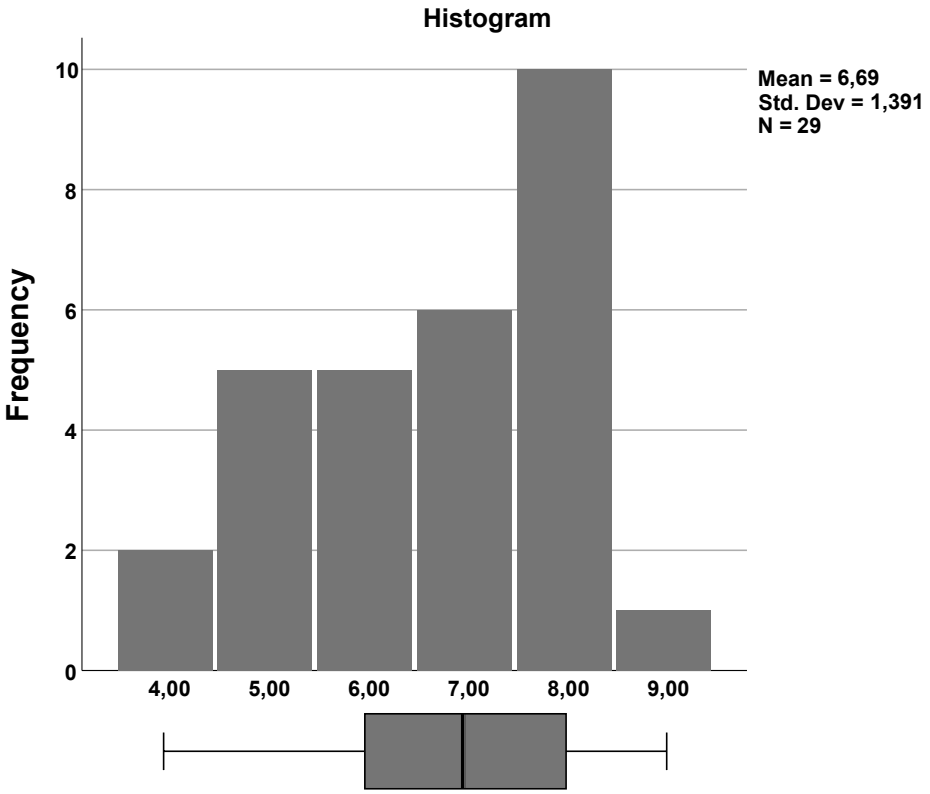

Fig. 2 Histogram with the quality assessment scores.

Table 5 Quality group for each analyzed paper.

Group	Studies
Low-Quality	[40, 22, 29, 35, 53, 34]
Medium-Quality	[43, 42, 12, 5, 38, 52, 49, 54, 3, 25, 14, 10, 9, 20, 28, 32, 24, 55, 53, 56, 46, 50]
High-Quality	[11]

4 Discussion

This systematic review aims to qualitatively and quantitatively survey and analyze all literature available. This literature review focuses on authoring tools to create immersive VR content. The goal is to provide knowledge about all available authoring tools, the context in which they are used, features and limitations.

The word cloud illustration (Figure 4) reveals that the most used terms of the analyzed record titles were: *Virtual Reality(16), 360 video(11), Authoring(7), Creation(5), Experiences(5), HMD(4), Multisensory(3), Maze(3), New(3), Editor(2), Mobile(2), Real-Time(2), Technique(2), User(2), Interaction(2) and Multiple(2)*. As

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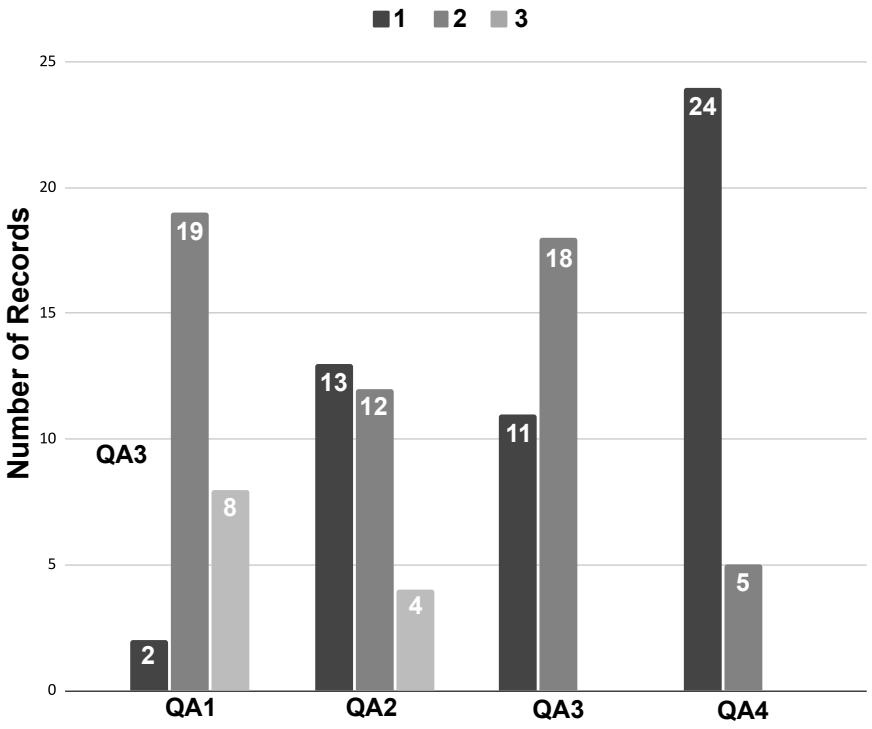

Fig. 3 Quality Assessment scores by quality factor.

one can see, the most frequent words shown by the word cloud are the ones that most resemble the research terms, such as Virtual Reality, HMD, Creation, Editor and Authoring.

The term Maze is a keyword that frequently appears and is not related to research terms. This keyword appears because some of the authoring tools created mazes to be used in VR. Likewise, the keyword Multisensory reflects that some authoring tools take into account multisensory stimuli to create VR experiences.

The Mobile keyword appears two times, the first record with this keyword presented an authoring tool inside a smartphone that uses the front camera of the device to create mazes, and the second time is an authoring tool that can be both used in an immersive system (HMD) or a tablet, both synchronized. The Multiple keyword also appears two times, but both records use this keyword to show that the authoring tool can create multiple immersive experiences. Real-Time keyword appears two times and means that the authoring tool allows the content visualization as it is created. Technique keyword was used when the authors referred to highlighting or masking techniques applied to 360 videos to highlight or mask particular objects. Interaction keyword was used when the authors evaluated different interaction methodologies (inside the 360 video or when creating the immersive content).

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Fig. 4 Word cloud based on analyzed records title.

4.1 What are the main application fields of the authoring tools?

Regarding the authoring tools' main application fields, Table 1 and Figure 5 show that most authoring tools were developed with no application field in mind, being considered General Purpose. Nonetheless, few authoring tools are developed to a specific application field, such as Graphical and Multimedia Designers [40, 14]; Gallery, Museum and Library Technicians [24, 55]; Construction Supervisors [35]; Mechanical Engineering Technicians [8]; and Medical Doctors [50]. We hypothesize that most authoring tools are General Purpose because those authoring tools are developed as a proof-of-concept and not developed with an application field in mind. These studies help users see the authoring tool's acceptance and find the main features they would like and expect to see in a finalized product, creating knowledge for the next iteration. It is worth noting that the Graphical and Multimedia Designers application field is used two times; this could happen because it is the area of application where the authoring of immersive content is most valuable. Also, the people who work in this application area start to notice the authoring tools' value/advantages. Gallery, Museum and Library Technicians is also an area of application where this type of authoring tools are being applied. This area of application is important to preserve and teach historical artefacts. Using VR experiences, users can learn about these new ways, popups with information or immersive videos explaining each artefact.

Research with a narrow focus creates knowledge about the acceptance of the authoring tools when applied to a specific application field. In addition, if they bring something useful, it makes the process easier or faster than other established methods.

4.2 Do authoring tools allow import/reuse of content?

As one can see in the Table 1, seven (7) of the analyzed records identified that the authoring tool **allow reuse/import of assets** [42, 12, 11, 38, 14, 8, 50], three

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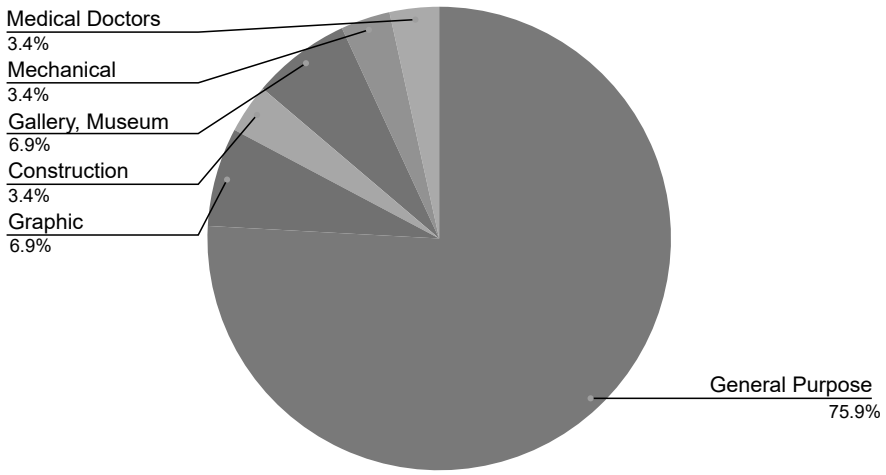

Fig. 5 Pie diagram with all application fields retrieved

(3) of them reported that the authoring tool does not support reuse/import of assets [54, 10, 32] and nineteen (19) of them do not report if they have or do not have this feature. One possible reason for not allowing the reuse/import of assets is to have more control over the experimental scenario. This controlled environment allows the authors to evaluate their authoring tool's usability and user satisfaction. Another possible reason could be that the reuse/import of assets is not the research's focus. Although reuse/import of content is not critical for evaluating the authoring tool, it is crucial for future commercial authoring tools since it allows users to reduce their work while also making customs experiences that otherwise would be impossible.

4.3 Was the authoring tool developed for experienced users?

Regarding users' knowledge, only five (5) authoring tools were evaluated by **specialized users** [38, 14], four (4) of them were not evaluated [40, 35, 8, 34], and the rest of the authoring tools was evaluated with users with no experience whatsoever (refer to Table 1). This may be because most of the developed authoring tools are designed to be used by non-expert users. When evaluating the authoring tools with non-expert users, the usability and satisfaction evaluation can be more precise since the users are not biased and used to perform specific actions in a certain way, being reluctant to changes in the processes they are used to execute. For example, envision an authoring tool to create 360º videos. Specialists are accustomed to a particular workflow that they gather along years of experience.

When it is meant for beginner users, evaluating a new authoring tool using specialists will cause low satisfaction due to being too simple or too different or not having much customization. However, on the other hand, if the authoring tool

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is designed to increase the specialists' productivity and efficiency on a specific task, evaluation has to be performed with these users since they are the ones that will use it.

4.4 What metrics and methods were used to evaluate the authoring tools?

Results show that not every authoring tool was evaluated. Puget et al. [40], Mo et al. [35], Cassola et al. [8], Mendes et al. [34] did not evaluate their authoring tools. One of the reasons behind such a decision was the lack of user control. The authoring tool presented by Puget et al. [40] creates a 360 Video of a VE where the physical camera controls the virtual camera, and the authoring tool presented by Mo et al. [35] is a data-driven authoring tool where a VE reacts accordingly to the data provided. However, the user is only a spectator unable to interact with the VE. Cassola et al. [8]' authoring tool was developed as a proof-of-concept with the intent to create VR experiences to train operatives. Mendes et al. [34]' authoring tool was another proof-of-concept with the intent to create 360 videos using XML tags. Instead of using users to evaluate the authoring tool, they only performed three case studies to see if it was ready to create the 360 videos. Every other authoring tool was evaluated with at least one of the following metrics: Usability, Effectiveness, Efficiency or Satisfaction. The first evaluates the user-perceived usability, meaning if they think the authoring tool was easy or difficult to use, if they encountered any problem with it, if they would use it again if needed, or even if they recommend it to other users. The second evaluates if users could finish a given task using the authoring tool's available tools. The third evaluates if the authoring tool is efficient to complete the task given to the user. The last metric measures the users' satisfaction while using the authoring tool. Usually, when evaluating an authoring tool, it is common to use all three metrics, mainly evaluated through observational data and custom questionnaires.

In both Table 2 and Figure 6, we can observe that most of the records analyzed used a Likert scale to analyze the above metrics. Coelho et al. [10, 12, 11], Torres et al. [46], Wilcocks et al. [50] used the System Usability Scale [6]; Coelho et al. [12, 11] used After-Scenario Questionnaire [30] to evaluate Satisfaction; Coelho et al. [12] evaluated presence using IGroup Presence Questionnaire translated and validated to Portuguese [47]; Gai et al. [20] used Post-Study System Usability Questionnaire [30]; Torres et al. [46] used Game Experience Questionnaire; and Wilcocks et al. [50] used User Experience Questionnaire. As one can see, there are well-established questionnaires to evaluate the authoring tools using various metrics, generating a more detailed and precise evaluation.

4.5 What were the stimuli used in the created content?

Regarding the use of stimuli, only five (5) studies implement other stimuli besides audiovisual [10, 11, 12, 14, 24]. Coelho et al. [10, 11, 12] integrated haptic and smell stimuli on the authoring tool and the experiences created by it, while Danieau et al. [14] and Khundam [24] only added haptic stimuli to the experience. Even though the record, in its majority, did not integrate any other stimulus, a few did (Table 3), showing that the introduction of stimuli into VR experiences can

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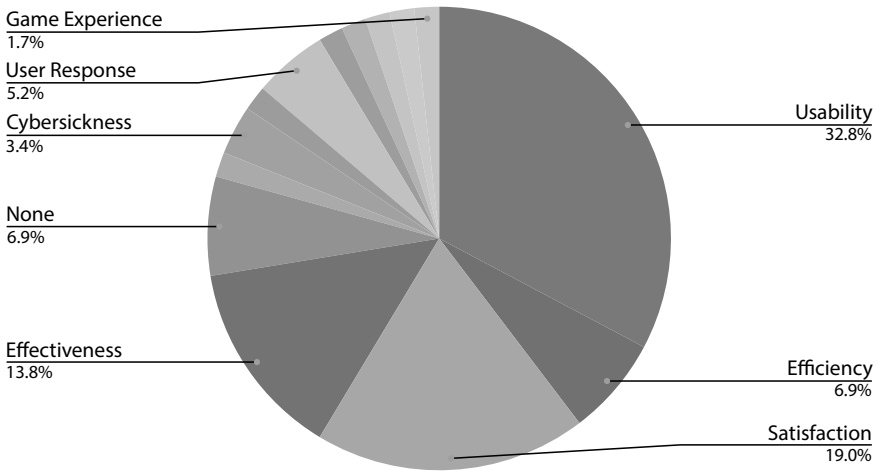

Fig. 6 Pie diagram with the percentage of each metric evaluated.

provide a better experience to the user. Also, the addition of stimuli coherently can increase the sense of presence that the user feels, making the VE more credible and consequently making users behave in the same manner as they would in the real world when exposed to similar experiences.

4.6 Features and limitations of authoring tools

The authoring tools features and limitations identified were various. Considering which type of content they were developed, one can see that most of the authoring tools were developed for creating 360 experiences. They were also studied how to focus the viewer attention to some regions of interest (ROI) [43, 42, 38, 32] or to create multisensory experiences [11, 12, 10].One must observe that even though the user can look freely in a 360 video, the important information can be missed. Thus, it is important to study different methodologies to tell users where the AOI is. On the other hand, multisensory authoring tools are developed to facilitate the creation of multisensory experiences. As proven by literature [10, 12, 11], multisensory experiences can improve users' sense of presence if done correctly. On all of these authoring tools, the limitations were mainly "the authoring tools only support 360 videos" and the problem of detecting objects for ROI. As for VE authoring tools, one can see that most of the authoring tools were developed to evaluate different interaction methodologies [29, 52, 49] or to create mazes [25, 20, 28]. This may happen since there is no established way to interact with the VE. These studies help developers identify what works or not when interacting with the VE. As for maze authoring tools are autonomous tools whose only purpose is to build mazes without any user input. With these maze authoring tools, the

developer does not need to focus on creating mazes. He only has to focus on the main aspects of the game, like interaction.

The works analyzed have two main tendencies: they only support predefined tasks and are developed to create mazes. The first was present if the study was about interaction methodologies. The second was properties about the maze: the maze should be a square, or the maze must be finite.

4.7 Do authoring tools adopt ontologies?

This subsection is not a research question, but the research team decided to see if any authoring tools used any ontologies. Ontologies should depict objects, interactions between objects, tasks, relations between objects, and restrictions so that both machines and humans can read them without any ambiguity between words. In the analyzed studies, none of them mentioned the usage of ontologies. Since all of them are considered proof-of-concept, none of the authoring tools has an ontology because making or using one and integrating it with the authoring tool can be hard or even require much work. That extra work might not be necessary to evaluate such authoring tools. If these authoring tools were developed as a final product, some would incorporate an ontology to simplify processes and have a well-defined structure. It is worth noting that not using ontologies could be considered a gap in the literature since its usage could mean that authoring tools are more consistent and reliable to the final user. On the other hand, ontologies could limit such applications because they can only be applied to that specific topic (depicted by the ontology). When developing an application, a decision should be made to whether an ontology should be included in the application (to limit its usage and to make it more consistent and reliable to the final user) or not include (making the usage of such an application broader but making the application less consistent and reliable).

4.8 Proposal of a Research Agenda

Based on the discussion above, it is possible to propose a research agenda for creating and developing a novel framework. The sole purpose of the framework is to create an immersive VE expeditiously. The following list will explain the research agenda to create such a framework.

- **Reuse/Import assets** - In-depth research about the re-usage/importation of assets will provide insight to new developers on whether the reuse/import of assets is necessary to the user when talking about immersive authoring tools.
- **Specialist evaluation** - Research about authoring tools being designed and developed to be used by experienced users needs to be evaluated. Whether or not there are any advantages in using experienced users to evaluate authoring tools compared to non-experienced users. Experienced users could prefer a specific way of doing tasks, and non-experienced users could prefer a different way.
- **Evaluation of authoring tools** - Further research needs to be done to reach a consensus of which questionnaires should be performed to evaluate certain

aspects of the authoring tools. This will allow a proper comparison between authoring tools, thus increasing the knowledge about what authoring tool features perform better.
- **Stimuli usage** - Depending on the task, adding other stimuli (smell or haptic) could improve the users' satisfaction and productivity regarding the authoring tool. However, more research needs to be done to see which tasks the addition of stimuli improves user satisfaction and productivity.
- **Ontology** - Usage of ontologies in authoring tools have not been addressed at all, as shown in this literature review. Ontologies could be a valuable contribution to a reliable authoring tool for the user to use, but no data could corroborate that.
- **Interaction methodology** - One crucial aspect of an authoring tool is the authoring tools' interaction methodology. Different methodologies could be presented depending on the task, giving the user multiple options to choose from. Moreover, hands-free interaction should be considered an option so that the user can perform multiple actions simultaneously.

5 Conclusion

This systematic literature review aimed to investigate the existing authoring tools, their intended purposes, their features and limitations, how they were evaluated, the evaluation metrics, and which stimuli they support. Furthermore, we studied the presence of ontologies and which were used.

5.1 Application Fields

Regarding the main application fields, only seven (7) of all authoring tools presented were developed for a specific application field. These seven were distributed within the following application fields: Graphical and Multimedia Designers application field (2); Gallery, Museum and Library (2); Construction Supervisors (1); Mechanical Engineering Technicians (1); and Medical Doctors (1). Even though they are developed for different application fields, they have been developed for specialized users. Because of this, we think that such users should evaluate the authoring tools. This would improve efficiency and reduce the time needed to create such VE. It would also mean that problems with usability would be easily found and fix such problems early in the development stage.

5.2 Assets Reuse

The feature of Reusing or importing assets is not the focus of the authoring tools analyzed since most of them do not specify this feature. However, this feature could significantly affect the authoring tool's usability, effectiveness, or satisfaction metrics. For example, the authoring tool could take a long time to import the desired asset or even not import all necessary data at all. The authoring tools that specify this feature only allow users to import predefined assets, thus assuring the proper importation.

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5.3 Evaluation Metrics

The metrics most used to evaluate the authoring tools were usability, efficiency, effectiveness, and satisfaction. Such metrics mainly were evaluated using the Likert scale on custom questionnaires taking into account MOS (Mean Opinion Scores). This approach has a limitation; if the authors do not mention the questions used, one does not know how each metric was evaluated and how reliable the data is. Besides custom questionnaires, some authors also used well-established questionnaires like SUS, IPQ, ASQ, PSSUS, GEQ and UEQ to evaluate the same metrics. Using such questionnaires, one can easily find the questions to evaluate and know that the data is reliable. One also knows that the questionnaire was previously validated through a scientific process. Data retrieved from well-established questionnaires also allows for better assumptions.

5.4 Stimuli

Visual and auditory stimuli are the most predominant stimulus among the authoring tools. Only five (5) of all authoring tools had other stimuli (smell and/or haptic) or allowed the addition of them into the experience. The addition of such stimulus can increase the users' sense of presence while making the VE more credible.

In short, there are opportunities to study the implications of reuse/import of assets on the usability/satisfaction of the authoring tools and also the implications on presence, cybersickness and satisfaction of using multiple stimuli to increase the sense of presence. Moreover, this survey's foremost opportunity is to study the effects of ontologies on authoring tools and, consequently, on the experiences developed. All retrieved data was organized into a searchable database, and it is available as supplementary material so readers can browse all the information freely.

The critical analysis of the literature has allowed proposing a research agenda envisaging the creation and development of a novel framework. The framework would be developed to create immersive virtual experiences expeditiously, taking full advantage of VR. The research team also considered all the variables collected in this systematic review and identified open research topics. Pursuing them would result in important contributions for the development of knowledge (refer to section 4.8 for details). The topics are: Reuse/Import assets into the framework; Specialist users for evaluation of the authoring tools; New metrics to evaluate the authoring tools; Usage of stimuli by the authoring tool to create more complete experiences; Addition of ontologies to the authoring tool; New interaction methodologies to be included in the authoring tools.

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Declarations

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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