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AUGMENTED REALITY IN THE TEACHING AND LEARNING PROCESS OF CHEMISTRY: A SYSTEMATIC LITERATURE REVIEW

REALIDADE AUMENTADA NO PROCESSO DE ENSINO E APRENDIZAGEM DE QUÍMICA: UMA REVISÃO SISTEMÁTICA DA LITERATURA

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ABSTRACT: Chemistry Education has been progressively complemented by pedagogical strategies involving the use of Augmented Reality (AR) technology. In this context, a systematic literature review was carried out in order to present the particularities of this scenario, such as those related to the technological scope, target audience profile, research methods, data collection instruments, number of students involved, and duration of the instruction. Forty-nine articles were analyzed, recovered from five databases, between the years 2011 to 2020. Among the main results found is the increase number of publications in the last three years, with the target audience of the studies being generally Secondary and Tertiary Education students (97.96%). Regarding technological aspects, the mobile platform and the marker-based system were predominant. In terms of methodology, the quantitative approach prevailed, together with the use of questionnaires as instruments for data collection. As for the number of participants, the experiments reported usually involved between 31 and 100 students, who had up to 60 minutes of instruction time. The article ends by revealing gaps in current research, presenting suggestions and directions for future work.

KEY WORDS: Augmented Reality. Chemistry Teaching. Educational Technology. Systematic Literature Review.

RESUMO: O Ensino de Química tem sido progressivamente complementado por estratégias pedagógicas envolvendo o uso de tecnologia de Realidade Aumentada (RA). Nesse contexto, foi realizada uma revisão sistemática da literatura com o objetivo de apresentar as particularidades desse cenário, como aquelas relacionadas ao escopo tecnológico, perfil do público-alvo, métodos de pesquisa, instrumentos de coleta de dados, número de alunos envolvidos e duração da instrução. Foram analisados 49 artigos, recuperados de cinco bases de dados, entre os anos de 2011 a 2020. Entre os principais resultados encontrados está o aumento do número de publicações nos últimos três anos, sendo o público-alvo dos estudos em geral alunos do Ensino Médio e o Ensino Superior (97,96%). Em relação aos aspectos tecnológicos, a plataforma móvel e o sistema baseado em marcadores são predominantes. Em termos de metodologia, prevaleceu a abordagem quantitativa, juntamente com a utilização de questionários como instrumento de coleta de dados. Quanto ao número de participantes, os experimentos relatados envolveram geralmente entre 31 e 100 alunos, que tinham até 60 minutos de aula. O artigo termina revelando lacunas nas pesquisas atuais e necessidades na área, apresentando sugestões e direcionamentos para trabalhos futuros.

PALAVRAS-CHAVE: Realidade Aumentada. Ensino de Química. Tecnologia Educacional. Revisão Sistemática da Literatura.

Introduction

Technological development has afforded new models of information dissemination, which are being increasingly introduced in teaching and learning processes. These models comprise attractive and innovative strategies, such as the implementation of resources that enable the connection of electronic devices to virtual and semi-virtual digital scenarios, such as Augmented Reality (AR) (Cadavieco et al., 2020). Azuma (1997) defines AR as a variation of Virtual Reality, characterized as a set of technologies that combines real and virtual images in real-time in an interactive way, making it possible to add virtual information to the physical information that the user perceives in the real world. Milgram and Kishino (1994), on their turn, define AR as a continuous scale from the real to the virtual environment. Because of its closeness to the real environment, it can be seen as an extended version of the real world, complemented by virtual objects. In this research, we assume that AR refers to all cases where the display of a real environment is increased by means of virtual objects.

Different learning domains are progressively being complemented by strategies involving AR. Antoniou et al. (2018), for example, developed a mobile AR application for Astronomy teaching, seeking to assist the learning of concepts and topics that require observational perceptions of students. Lim and Lim (2020) used AR on mobile devices in the discipline of History, addressing the challenges of accurately recalling historical facts. Kaur et al. (2020) employed AR as an interactive learning tool in various fields of Engineering education, in an attempt to improve students' motivation. Numerous works involving AR have also been carried out in fields such as Mathematics (Pérez-Muñóz et al., 2020), Physics (Abdusselam & Karal, 2020), Biology (Celik et al., 2020), and Chemistry (Nechypurenko et al., 2020).

Chemistry is a particular discipline which deals often with abstract concepts, posing great challenges for students in understanding the microscopic and macroscopic chemical world (Cai et al., 2014). These concepts involve complex issues, such as molecular structures (Maier & Klinker, 2013), chemical bonds (Wan et al., 2018), and chemical reactions (Ewais & Troyer, 2019). In this context, AR has been used to help students understand these concepts, mainly because it provides users with an environment of coexistence between reality and virtuality (Lin et al., 2015). In this context, this Systematic Literature Review (RSL) aims to deepen the knowledge related to the applicability and relevance of Augmented Reality in the teaching of Chemistry, revealing the properties of this technology, as well as the particularities of the target audience and assessment methodologies.

Investigating studies in a specific field is essential to expose the current situation and shed light on future studies (Sirakaya & Sirakaya, 2018). In the last decade, the use of AR in teaching and learning processes has been the subject of numerous researches, which has been reported in systematic reviews. These reviews sometimes focus on the target audience, research method and types of AR used (Bacca et al., 2014), to report the number of participants and length of instruction (Ibáñez & Delgado-Kloos, 2018), to identify how AR has been evaluated in education (Silva et al., 2019), or even to analyze articles that compared environments with or without the use of AR (Radu, 2014). Although these aspects have been identified in the literature, there are no systematic reviews specifically related to the use of AR in Chemistry, creating a knowledge gap that requires further exploration. Therefore, this work seeks to contribute to filling this gap, analyzing and categorizing articles by target audience profile, platform and type of AR system used, research methods, data collection instruments, number of students involved, and duration of the instruction.

Methods

This work followed the Systematic Literature Review process defined by Kitchenham (2004). The protocol was reviewed by a doctor and a doctoral student in Informatics in Education, as well as by a doctor in Computer Science, all of whom had more than eight years of scientific experience with Virtual Reality and Augmented Reality. The execution was divided into three main phases: planning, conducting and reporting, according to the phases described in the following sections.

Planning

In this stage, the secondary research questions were defined, as well as the search string, in an attempt to respond to the main research question: "How has AR been used in the Chemistry teaching and learning processes?". Initially, there was an effort in trying to answer the research question in a broader way, by segmenting it in a varied set of secondary questions. However, during the analysis of the articles selected in this SLR, expressive results were revealed, guiding the study to new directions. Thus, the research path was two-folded, with results published in (*omitted for blind-review purposes*), focusing on the main topics of Chemistry in which AR is applied, as well as the advantages and disadvantages of its use, and the research questions (RQ) below, addressed in this study:

RQ-1. What are the target audiences of the studies?

RQ-2. What types of platforms are used?

RQ-3. What categories of Augmented Reality systems are used?

RQ-4. Which research methods are used?

RQ-5. What instruments are used to collect data?

RQ-6. How many students are involved in the studies?

RQ-7. What is the duration of the instruction period involving Augmented Reality?

To present the target audiences of the studies (RQ-1), the levels of education proposed by the International Standard Classification of Education – ISCED (UNESCO, 2011) were considered. RQ 2 and 3 are related to the technical aspects of using AR. RQ-2 seeks to identify the type of platform used, following the model proposed by Bosch (2009), in terms of the dominant computing platform, that is, "Desktop", "Web" and "Mobile"; and to classify AR (RQ-3), the proposal by Wojciechowski and Cellary (2013) was considered, who defined the types as being "Location-based'', "Marker-based", and "Markerless".

To identify the research methods used (RQ-4), "Quantitative", "Qualitative", and "Mixed" approaches were assumed. Also, following perspectives consistent with the research, RQ-5 verifies which instruments are used to collect data on learning, RQ-6 reports the number of students involved in the studies, and RQ-7 analyzes the duration of instruction.

To retrieve the articles, a search string was defined considering the main aspects investigated: ("augmented reality" OR "mixed reality") AND chemistry AND (teaching OR learning). These keywords had to appear together (in the same document), although in any field (title, abstract, full text, etc.). A representative time interval of ten years was defined, from 2011 to 2020.

Conducting

The conduction of this SLR took place between January and February 2021, being updated in September and October 2021. Data collection from primary studies were peer-reviewed in two moments, namely: in the first week of January and in the last week of September. Five digital databases were selected, for being academically and scientifically renowned, recognized as significant and reliable sources that index high-quality publications: Web of Science, Scopus, ScienceDirect (Elsevier), ACM Digital Library and IEEE Xplore Digital Library. The official search engines of these databases were used to retrieve the articles, by using the aforementioned keywords.

To be included in the review, each article had to present a study involving real participants, in which AR was implemented in practice, being, in some way, related to the teaching and learning process in the field of Chemistry. In this context, each paper also had to present some type of evaluation with end-users. The Inclusion Criteria (IC) and the Exclusion Criteria (EC) defined to evaluate the studies are presented in Table 1. It is relevant to note that the EC were self-excluding, that is, if an article was rejected by any given criterion, the subsequent EC were not considered and the article was excluded from the review.

Table 1: Inclusion and exclusion criteria.

Inclusion Criteria (IC)	
IC-1	The study presents an application of AR in the teaching and learning process of Chemistry.
IC-2	The study presents some type of evaluation with end-users.
Exclusion Criteria (EC)	
EC-1	The study is gray literature or non-peer-reviewed publication.
EC-2	The study is secondary, whether it is a review, a meta-analysis, a survey, or it is a philosophical or theoretical work.
EC-3	The study is written in a language other than English.
EC-4	The full text of the study is not available.
EC-5	The study shows no application of AR in the teaching and learning of Chemistry.

Source: Elaborated by Authors.

The process of conducting this SLR was divided into three main phases, described as follows.

Phase 1, Search: it comprised the retrieval of information, through the insertion and execution of the search string in the five databases. The records resulting from the searches carried out in each database were exported to BibTeX files. The records in BibTex were imported to the free web tool Parsifal (https://parsif.al) in order to remove duplicate articles, to classify entries by database, and to export results to a spreadsheet, which was used in the next phases. The selection of documents considered articles that were published both in peer-reviewed journals and conferences, as well as in peer-reviewed book chapters.

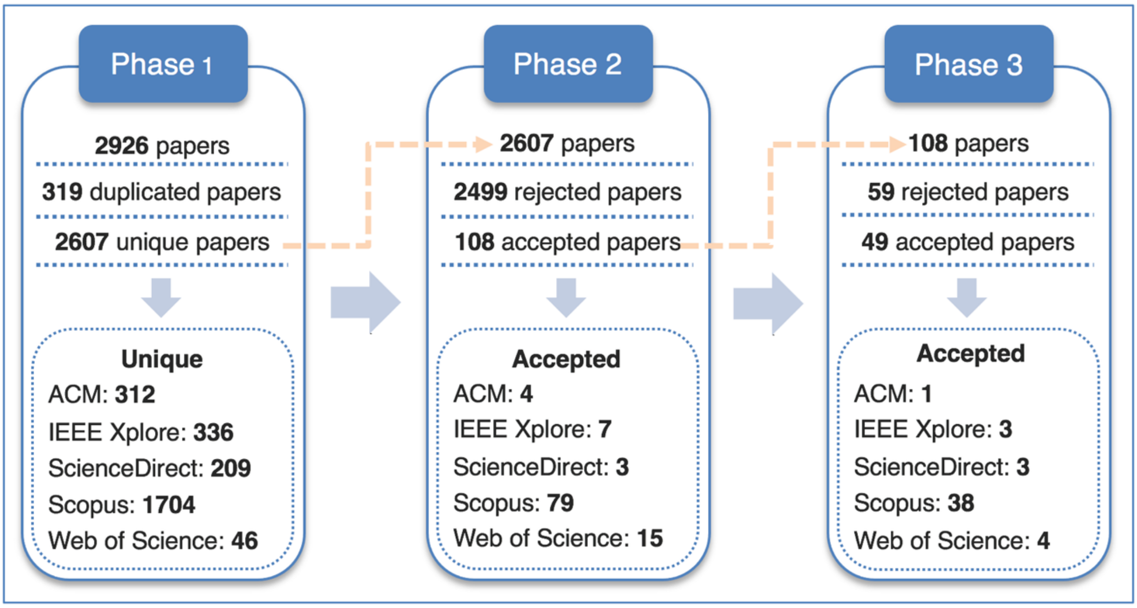
Phase 2, Selection: it involved reading the title, abstract, and keywords of each retrieved paper, confronting it with the IC and EC. No particular quality assessment procedure was used. Nevertheless, inclusion criteria IC1 and IC2 assisted us in selecting publications that did report on some use of research methods to evaluate the use of AR with students in Chemistry education. Every article was individually analyzed by two researchers. In order to account for inter-reliability issues, in the event of a discrepancy of opinions, the responsibility for the final verdict regarding the selection of articles lied with a third senior researcher. At this stage, Google Sheets was used as a support tool. Spreadsheets shared among the researchers were created, containing a set of information from the articles, allowing reviewers to directly and systematically access each paper and immediately inform their opinion, in a simple, objective, and consistent way.

Phase 3, Extraction: it consisted in the full reading of each article accepted in the previous phase, confronting it again with the IC and EC. The same procedure of the second phase was maintained here, in which the studies were reviewed by peers, with the decision of a third researcher in cases of disagreement. Finally, primary studies with the potential to generate answers to the research questions were accepted. This phase was carried out with the support of Google Forms. An online form was created containing the eleven research questions, with closed and open answers, as in a checklist, with the aim of making the data extraction and analysis procedure more consistent and objective. The reviewers could edit their responses, allowing actions such as correction, removal, and addition of information.

Reporting

At the end of the searches in the databases, carried out in Phase 1 (Search), 2926 studies were found. From these, 319 were duplicated, i.e. the exact same articles were returned from more than one repository. After removing them, 2607 unique papers remained. In Phase 2 (Selection), 2499 records were rejected and 108 accepted. The 108 selected papers were reviewed again in Phase 3 (Extraction), in which 59 were rejected and 49 were accepted. These 49 articles formed the set of primary studies analyzed in this SLR (see Appendix I: https://cutt.ly/OUwkicL). The flowchart presented in Figure 1 summarizes the results obtained in each phase.

Figure 1: Flowchart of the SLR conduction.



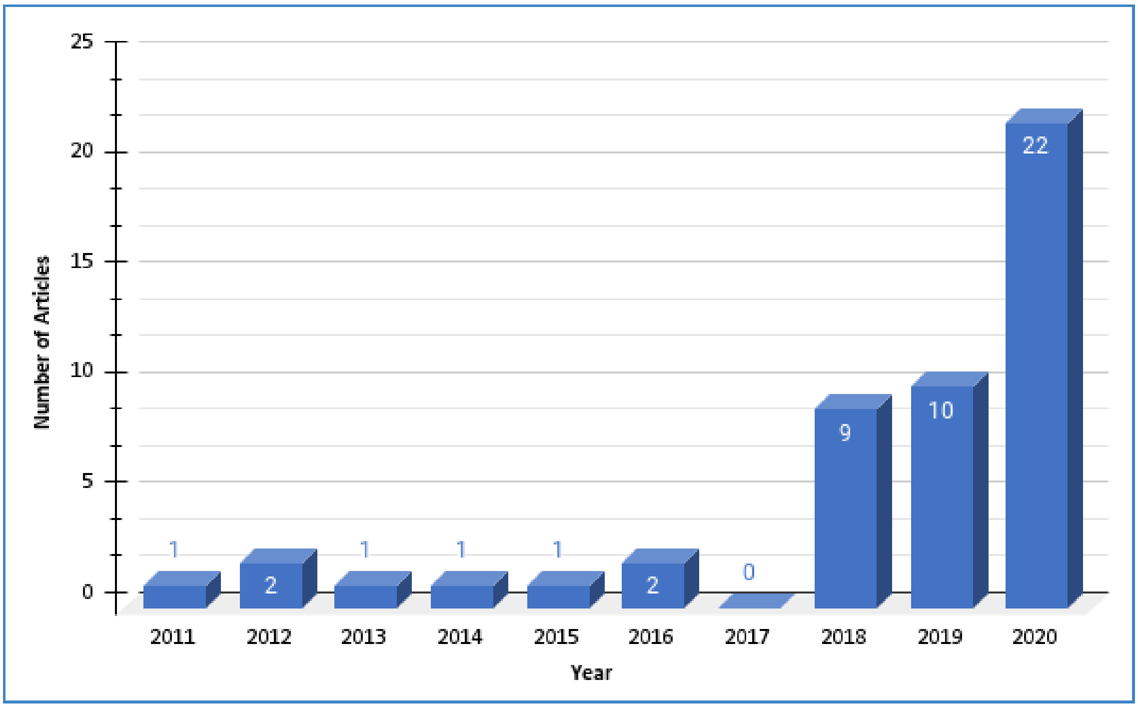
Source: Authors.

Figure 1 shows that Scopus returned 1704 unique publications in the initial search, representing the majority of articles finally accepted (38, 77.55%). Subsequently, four articles were returned from the Web of Science (8.16%), and six articles were returned from the IEEE Xplore Digital Library and ScienceDirect (three articles each, 6.12%). Finally, one article (2.04%) was returned from the searches in the ACM Digital Library.

Results and Discussion

Figure 2 shows the distribution of publications over 10 years, showing a significant rise in AR studies as a part of the Chemistry teaching and learning process in the last three years. This scenario is in line with Garzón et al. (2019) and Sırakaya and Sırakaya (2020), who affirm that there has been a constant increase in the use of AR in Education. This growth can be explained by the increasing spread of mobile devices in educational environments (Ewais & Troyer, 2019), as well as by the progressive expansion of these devices' processing capacities (Hanafi et al., 2019).

Figure 2: Studies distribution over the years.



Source: Elaborated by Authors.

The next sections present results and discussion corresponding to each RQ proposed. The studies used as examples to support and clarify the analyses prioritized the most recent publications.

RQ-1. What are the target audiences of the studies?

Considering that the studies originated from different countries, with different terminology and age ranges for each educational stage, an effort was made to categorize the target audience by the degree of proximity of the students' age (when mentioned) in the levels of education proposed by ISCED (UNESCO, 2011). After the categorization, shown in Table 2, it is possible to notice that the target audience is concentrated, essentially, at the Secondary Education and Tertiary Education levels.

Table 2 shows that 51.02% of the articles were targeted at Lower Secondary Education (12.24%), Upper Secondary Education (34.69%), or Multiple (covering more than one level) (4.08%), corroborating the literature review carried out by Ibáñez and Delgado-Kloos (2018), that investigated AR technology to support the learning of Science, Technology, Engineering and Mathematics (STEM). Equally representative, the Tertiary Education level was the target audience of 46.94% of the articles, similarly to the work of Sirakaya and Sirakaya (2018), which searched for trends in educational studies that used AR and found that most studies contemplated this educational level. Finally, Primary Education was considered by only one paper (2.04%).

To exemplify, the study of Badilla-Quintana et al. (2020) had as target audience students from Upper Secondary Education, and used the AR VR Molecules Editor application for Chemistry classes; the main results showed significant improvement in immediate academic performance and content retention. Zhang, Li, Chang et al. (2020), on their turn, designed and implemented an interactive AR-based experimental course on electrolyte cells in Chemistry with Lower Secondary Education students and concluded that interactive AR-based experiential teaching can improve students' cognitive ability. The research by Macariu et al. (2020) involved students from both Lower Secondary Education and Upper Secondary Educationd (Multiple), and proposed a new system, called ARChemistry Learning, to support the Romanian educational system. Key findings of this study indicate that AR supports traditional teaching methods, increases attractiveness, helps in more easily retaining new information, and improves the interaction between students and teachers.

Aw et al. (2020) designed and developed a mobile application, which uses AR, called "Nucleophile's Point of View" (NuPOV). The work involved Tertiary Education students and as a result, they concluded that RA improves interest and willingness to learn, facilitates learning and increases confidence. The research by Olim and Nisi (2020) targeted Primary Education students, who used the serious AR game "Periodic Fable", designed to teach basic concepts of Chemistry (elements of the periodic table) in non-formal environments. They obtained as findings that AR facilitates the understanding of Chemistry, supports the learning of abstract concepts and increases curiosity in relation to other chemical elements.

From an educational perspective, the concentration of studies at these levels is possibly a particularity of the Chemistry discipline, more than any other factor related to the AR technology itself. As discussed at the beginning of this text, Chemistry is a very complex area of knowledge, in which learning requires prior knowledge in Sciences, such as notions of Physics and the concept of matter, which enable the understanding of modern Chemistry.

Table 2: Target audience of the studies.

Level of Education	Studies	(%)		Sample Research
Primary Education	1	2.04		Olim and Nisi (2020)
Lower Secondary Education	6	12.24	51.02	Zhang, Li, Chang et al. (2020)
Upper Secondary Education	17	34.69		Badilla-Quintana et al. (2020)
Multiple	2	4.08		Macariu et al. (2020)
Tertiary Education	23	46.94		Aw et al. (2020)
Total	49	100		-

Source: Elaborated by Authors.

It is also possible to argue, from a biological development perspective, that studies involving the target audience of Secondary Education level are in higher numbers also because students at this level are in transition between the Concrete Operative Stage and the Formal Operations Stage, as proposed by Piaget (1976). In the first stage, the student is in the process of developing the notion of time and space beside the ability to abstract reality, depending a lot on the concrete world (models) to reach abstraction. In the second stage, the capabilities gained in the previous stages are expanded; the individual is able to think of all possible relationships based on hypotheses that do not necessarily depend on the immediate observation of reality. In this scenario, AR can be a useful tool to facilitate the understanding of abstract concepts (Virata & Castro, 2019; Olim & Nisi, 2020) in Chemistry, especially in applications at the Secondary Education level. In this sense, the fact that, according to Huitt and Hummel (2003), only 35% of high school graduates in industrialized countries are capable of performing formal operations, and that many people do not think formally during adulthood, this could also explain the high number of studies involving the Tertiary Education level. Thus, learning tools using technologies such as AR can help develop cognitive skills during this period (Zhang, Li, Chang et al., 2020), allowing the visualization of invisible concepts and events (Cen et al., 2019). Perhaps for this reason, as well as in Secondary Education levels, Tertiary Education is also a target audience with great relevance; adding the two levels together, there is a total of 97.96%.

RQ-2. What types of platforms are used?

The model proposed by Bosch (2009) was adopted to identify the type of platform used in the AR applications in Chemistry, which is oriented towards dominant terms of computing platforms, such as "Desktop", "Web" and "Mobile". To complement it, the categories "Others" and "Not informed" were added. Table 3 shows that Mobile is the type of platform most used, being present in 36 articles (73.47%), followed by Desktop (6, 12.24%) and the Web platform (2, 4.08%). Three studies did not explain the type of platform used, or did not provide enough or explicit information for proper identification, being classified as "Not informed" (6.12%). Finally, two works were classified as "Other" (4.08%).

Gan et al. (2018) reported the application of an AR tool using a Web platform, to work with the generation of oxygen. As a result, they concluded that AR facilitates learning, increases confidence, allows the safe simulation of dangerous experiments and reduces costs (equipment and laboratory supplies). On the other hand, the research by Zhang, Li, Han et al. (2020) used a multimedia environment structure with AR focused on the Desktop platform to teach the topic of Thermite Reaction. The authors pointed out that AR can effectively improve educational activities, enhance the effects of teaching, and improve students' interest in experiential learning.

The Web platform was used in the study of Satpute and Bansode (2016), involving the design and development of a set of AR learning tools to work with "the NMR spectroscopy of hydrocarbons". Through data analysis and discussion, the authors concluded that AR had a significant supplementary learning effect. The platform used by Iordache et al. (2012), classified as "Other", involves the ARiSE project, which implements a Chemistry learning scenario based on the "build with guidance" interaction paradigm; they concluded that AR improves performance and facilitates learning. Finally, the research by Wulandari et al. (2019), which aimed at analyzing learning using AR media to develop the ability of submicroscopic representation, does not define the type of platform. However, the results indicate that AR allows the visualization of invisible concepts, events and abstract concepts.

Table 3: Types of platforms in which AR is being used in the studies.

Platform Types	Studies	(%)	Sample Research
Desktop	6	12.24	Zhang, Li, Han et al. (2020)
Mobile	36	73.47	Gan et al. (2018)
Web	2	4.08	Satpute and Bansode (2016)
Other	2	4.08	Iordache et al. (2012)
Not informed	3	6.12	Wulandari et al. (2019)
Total	49	100	-

Source: Elaborated by Authors.

The results presented at Table 3 corroborate the study of Alseadoon et al. (2021), in which they claim that in recent years research and development efforts have focused on the systematic migration of existing software systems to mobile computing platforms, allowing these systems to achieve characteristics such as portability, context-sensitivity, and high enhanced connectivity. Likewise, it is possible to relate this result to the scarce Mobile resources observed a few years ago, when applications were not considered easily viable to run on these devices; a scenario that has been changing with the increasing global technological development (Ewais & Troyer, 2019).

According to Hanafi et al. (2019), modern devices adequately support applications that demand a significant amount of computational resources, such as the AR technology.

RQ-3. What categories of Augmented Reality systems are used?

The study of Wojciechowski and Cellary (2013) classified AR systems into three categories: “Location-based”, “Marker-based”, and “Markerless”. According to this proposal, location-based AR systems use the positioning data from mobile devices, determined by Global Positioning System (GPS) or WiFi-based positioning systems. Marker-based systems require the use of artificial markers in the real environment, and the “Markerless” category is based on the tracking of natural characteristics of physical objects present in the real environment. The “Not informed” category was included to classify studies that did not specify the AR system used.

Since no article was classified as “Location-based”, this category was removed from the final classification, summarized in Table 4.

Table 4: Categories of AR systems being used in the studies.

Categories	Studies	(%)	Sample Research
Marker-based	44	89.80	Wan et al. (2018)
Markerless	4	8.16	Ovens et al. (2020)
Not informed	1	2.04	Kodiyah et al. (2020)
Total	49	100	-

Source: Elaborated by Authors.

The results show that the Marker-based AR system was the most used, being present in 44 studies (89.80%). These expressive numbers are in line with the surveys of Bacca et al. (2014) and Sirakaya and Sirakaya (2018), in which they identified that the majority of the studies analyzed, 59.3% and 86% respectively, used the Marker-based type. This result is also emphasized by the study of Jiménez (2019), who affirmed that most AR projects explored in areas such as Chemistry use markers to generate virtual information superimposed in the real world. One plausible explanation for this finding is related to the marker tracking process, which is better and more stable compared to the Markerless tracking techniques (Satpute and Bansode, 2016). In addition, it allows fixing the image in the marker for it to remain stable while the device’s camera reads it, enabling the user to correctly observe the 3D images from various angles (Virata & Castro, 2019).

Wan et al. (2018) used an AR mobile app, categorized as Marker-based, developed for Chemistry classes with a focus on the redox reaction; the results showed that AR improves performance, increases motivation and facilitates learning. The four studies in the Markerless category (6.98%) had unique characteristics in their AR systems. An example is the work of Ovens et al. (2020), who presented a DNA precipitation app, in which 3D images were generated in a previously digitized horizontal plane; they identified that the students prefer to use this type of technology as a reflective tool to consolidate their laboratory experience. Finally, the Not informed category had only one occurrence (2.04%), referring to the research of Kodiyah et al. (2020), who applied an AR media to improve students' spatial ability in alkanes and cycloalkanes conformation. They results obtained reinforced the idea that AR facilitates learning and contributes to the development of spatial ability.

RQ-4. Which research methods are used?

To identify the research methods used in the publications, the “Quantitative”, “Qualitative”, and “Mixed” approaches were considered (Williams, 2007). As most studies (more than 60%) did not explicitly state the methodology used, with an absence of details related to the methodological processes, a detailed analysis of each article was carried out. In this sense, an attempt was made to identify the methodology by approximation, which was inferred and discussed by the reviewers.

Thus, the most used method was Quantitative (Table 5), present in 29 articles (59.18%). The second most used method was Mixed, used in 16 studies (32.65%), followed by Qualitative, adopted in 4 articles (8.16%). These proportions are similar to those found in the survey of Ibáñez and Delgado-Kloos (2018), in which 46.4% of the studies on the use of AR in STEM education used a Quantitative approach; followed by 35.7% that used a Mixed approach, and 17.9% that used a Qualitative approach. Likewise, these results are close to the ones presented by Sırakaya and Sırakaya (2020), with the Quantitative methodology present in the majority of studies (52%), followed by Mixed (43%), and Qualitative (5%) approaches.

Table 5: Categories of AR systems being used in the studies.

Methods	Studies	(%)	Sample Research
Quantitative	29	59.18	Cen et al. (2019)
Qualitative	4	8.16	Swamy and Dasgupta (2018)
Mixed	16	32.65	Ewais et al. (2019)
Total	49	100	-

Source: Elaborated by Authors.

To exemplify the Quantitative method, the research of Cen et al. (2019) aimed at presenting a mobile educational system based on AR to help students learn the basics of molecular Chemistry. The results revealed that AR can play a role in reinforcing the retention of critical knowledge, working directly on students’ knowledge gaps. Ewais et al. (2019) used Mixed methods to investigate the students' attitude towards the use of a mobile AR application for learning the reactions of atoms and molecules. The authors found that AR can help students understand microscopic structures, as well as possible interactions between different atoms and molecules.

Although it can be argued that quantitative methods have advantages, such as the generalization of results (Sırakaya & Sırakaya, 2020), the small number of publications based on Qualitative methods was unexpected. Only four articles referring to this approach were found, such as the study of Swamy and Dasgupta (2018), which reported a research on the use of an AR-based molecular visualization application to investigate how Chemistry students, from different grades, connect the structure and properties of stereoisomers. In conclusion, the authors suggested key design guidelines for curriculum design, pedagogical practices, and technology support.

RQ-5. What instruments are used to collect data?

The instruments used for data collection were identified and classified into five types, as shown in Table 6. Since 23 studies (46.93%) used two or more types of instruments, a total of 87 occurrences of instruments throughout the 49 analyzed studies were identified.

The most used type of data collection instrument was the Survey questionnaire, with 38 occurrences (43.68%), followed by the Performance test, present in 22 works (25.29%). The preference related to the Survey questionnaire is consistent with the literature review carried out by Santos et al. (2014), whose results indicate a popularization of this type of instrument for data collection. However, when comparing these results with those of the surveys carried out by Sırakaya and Sırakaya’s (2018) and Dey (2018), there is an inversion in the order of the first two places, in which the type with the highest use is the Performance test, followed by the Survey questionnaire.

Table 6: Types of instruments being used for collecting data in the studies.

Data Collection Instrument	Studies	(%)	Sample Research
Interview	10	11.49	Woźniak, Lewczuk, Adamkiewicz, Józiewicz, Jaworski et al. (2020)
Observation	10	11.49	Nurrohmah et al. (2020)
Performance testing	22	25.29	Asai and Takase (2011)
Survey questionnaire	38	43.68	Schmid et al. (2020)
Others	7	8.05	Habig (2020)
Total	87	100	-

Source: Elaborated by Authors.

The sum of the types Survey questionnaire and Performance test represents a proportion of more than 60%, indicating a tendency for their use in the literature. A possible explanation for this result can be found in a relationship with the most used research method (Quantitative, with an index of 59.18%, RQ-4), in which the instruments Survey questionnaire and Performance test would be largely contemplated. In this regard, it is common to observe the application of questionnaires and tests composed of objective questions, with a large part of these studies making use of the Likert scale, as seen in the works of Aw et al. (2020), and Chen and Liu (2020).

Schmid et al. (2020), for instance, present an implementation of AR projections for the representation of complex structures, including atomic orbitals and elementary allotropes. As a data collection instrument, they used a Survey questionnaire (5-points Likert scale) and concluded that it improves student performance. From another perspective, Asai and Takase (2011) analyzed the characteristics of using a tangible table produced with AR to improve the perception of students of the environment in which they had to observe three-dimensional molecular structures. They used performance tests to collect data, and revealed that AR, in addition to improving performance, provides realistic interactions and facilitates molecular visualization.

Subsequently, both with 10 occurrences each (11.49%), are the instruments Interview and Observation. These proportions are close to the survey of Sırakaya and Sırakaya (2018), in which the types of instruments Interview and Observation were identified, respectively, at the rates of 13.3% and 9%. The Observation instrument was used in the study of Nurrohmah et al. (2020), which aimed at evaluating the improvement of students' understanding of concepts in learning tasks of sharing electrolytic and non-electrolytic solutions. As a result, the authors concluded that AR improves understanding. On the other hand, Woźniak, Lewczuk, Adamkiewicz, Józiewicz, Jaworski et al. (2020) used interviews in a research aimed at the application of a laboratory task management tool called ARchemist. The authors noted that AR facilitates learning, increases confidence, and is suitable for lab courses.

Other types of instruments used for data collection, such as Group discussions, Reflections from the teacher's diary (Virata & Castro, 2019), and Tests of spatial ability (Habig, 2020) were present in a total of seven studies (8.05%).

RQ-6. How many students are involved in the studies?

The number of students who participated in studies that used AR in the teaching and learning process of Chemistry had great variability. The study of Woźniak, Lewczuk, Adamkiewicz, Józiewicz, Malaya et al. (2020), for instance, involved only two participants, the lowest number identified. The research by Abdinejad et al. (2020), on the other hand, comprised 302 participants, the highest number identified among the 49 studies analyzed. Table 7 shows that 21 studies (42.86%) had a sample in an interval between 31 and 100 participants, such as the work of Estudante and Dietrich (2020), that had the participation of 70 students. In this research, the authors provided an AR application for educational activities involving equilibrium equations, molar calculations and Leblanc/Solvay processes. They pointed out, as the main conclusion, that AR increases students' motivation.

Table 7: Number of students involved in the studies (sample sizes).

Sample Size	Studies	(%)	Sample Research
Between 1 and 10	8	16.33	Tee et al. (2018)
Between 11 and 30	10	20.41	Nazar et al. (2020)
Between 31 and 100	21	42.86	Estudante and Dietrich (2020)
Between 101 and 300	4	8.16	Chen and Liao (2015)
More than 300	1	2.04	Abdinejad et al. (2020)
Not informed	5	10.20	Rubilar (2019)
Total	49	100	-

Source: Elaborated by Authors.

These values are in line with Sırakaya and Sırakaya's (2020) survey, in which 69.05% of the studies that used AR to support STEM teaching had sample sizes in this same interval. Approximate values were also found by Ibáñez and Delgado-Kloos (2018); they identified that most AR research in education involved less than 90 participants (75%). Likewise, the results are in agreement with the work of Chen et al. (2017), which found that most studies had "average" sample sizes between 30 and 200 members. It is possible to consider that this scenario is in line with the recurrence of both Quantitative methodologies (RQ-4) and data collection instruments of the type Survey questionnaire (RQ-5), which according to Sırakaya and Sırakaya (2018) are generally used to identify the effects of AR technology in education.

Subsequently, ten studies (20.41%) comprised between 11 and 30 participants, such as the work of Nazar et al. (2020), which had the participation of 17 students. This study aimed to develop and apply an AR App used for the learning of molecular geometry, obtaining as main finding the ease of use. The range of one to 10 participants was present in eight articles (16.33%), among them the study of Tee et al. (2018), with 10 students. The authors of this research described and demonstrated an AR colorimetric titration tool that operates from a student's smartphone or tablet, and concluded that it allows the safe application of dangerous experiments while reducing the costs of laboratory equipment and supplies.

Therefore, a 36.74% rate of articles had a relatively small number of participants in their experiments (less than 30). This can be a limiting factor, especially when attempting to generalize results, or, according to Sirshar et al. (2019), to provide accurate results. The range of 101 to 300 participants included four studies (8.16%), such as Chen and Liao (2015), with 152 students. The authors' aim was to investigate the effects of AR types and guidance strategies on student performance and motivation in electrochemistry concepts. The authors concluded that AR directly increases motivation. Finally, five studies did not report the number of participants involved (10.20%), such as Rubilar (2019).

RQ-7. What is the duration of the instruction period involving Augmented Reality?

Table 8 shows that most studies (67.35%) did not express the duration of instruction time, as in the case of Fitriani et al. (2019). This is possibly because this information is not considered essential and, perhaps, it is understood as being complementary. However, this lack of information hinders the complete understanding of the study and makes it impossible to replicate it.

Table 8: Duration time of the instructions in the studies.

Instruction Duration	Studies	(%)	Sample Research
Up to 60 minutes	9	18.37	Cai et al. (2014)
Between 61 and 120 minutes	2	4.08	Maier and Klinker (2013)
Between 121 and 1320 minutes	2	4.08	Acosta et al. (2019)
More than 1320 minutes	3	6.12	Saidin et al. (2019)
Not informed	33	67.35	Fitriani (2019)
Total	49	100	-

Source: Elaborated by Authors.

The survey carried out by Ibáñez and Delgado-Kloos (2018), for example, is one of the few that states explicitly the instruction time, finding that most studies were conducted in a single session, ranging from 7 to 180 minutes. These numbers are close to those presented in Table 8, which indicates that most studies (11) that did report the duration of instructions are in the first two intervals (up to 120 minutes).

Subsequently, nine studies (18.37%) had instruction time in a period of up to 60 minutes, such as the work of Cai et al. (2014), with 40 minutes. This work aimed at analyzing the use of a set of AR learning tools in the topic of "composition of substances", and the authors concluded that AR has a significant supplementary learning effect, as well as being more effective for low-achieving students than high-achieving students.

Two articles (4.08%) were classified in the range between 61 and 120 minutes. One of them is the study of Maier and Klinker (2013), in which the instruction period was of 70 minutes. The authors investigated the hypothesis that the understanding of the spatial structures of molecules is enhanced by AR-based 3D user interfaces, and concluded that this technology develops spatial ability, improves performance, and facilitates learning. In the interval between 121 and 1320 minutes there is also two studies, one of which is the research by Acosta et al. (2019), which had 1200 minutes of instruction time. They presented and evaluated a framework for designing motivational AR applications, and revealed that this technology increases motivation, improves willingness to learn and develops cognitive skills.

Finally, with a time-range longer than 1320 minutes there were three studies (6.12%), such as the research of Saidin et al. (2019), which lasted four weeks. They presented a framework for the development of Mobile AR for the learning of chemical bonds, as well as the application of a system following this structure. The results allowed them to conclude that AR improves student performance on this topic.

Limitations and Future Work

The main limitations of this SLR are related to the selection of databases and keywords. Regarding the databases, although they are representative of a significant collection of high-quality scientific indexing systems, the search was limited to analyzing articles indexed in five repositories: ACM Digital Library, IEEE Xplore Digital Library, ScienceDirect (Elsevier), Scopus, and Web of Science. The use of a specific set of keywords also implies that publications that used different indexing words might have been excluded.

The shortcomings and gaps identified in this work point to several research topics of interest for future studies:

- Several aspects that could broaden the understanding of elements related to the application of AR in the teaching and learning process of Chemistry were not considered in this study, such as country in which the experiments were carried out, location (classroom, laboratory, or external environment), type of study (formal, pilot, heuristic or field), and instructional strategies (discovery, presentation, and cooperative/collaborative);
- Technical aspects specific to the AR systems could also be further analyzed, such as libraries and/or engines used, programming languages, types of files that contain the descriptions of the object scenes (e.g. VRML, X3D, or glTF), and type of rendered image (image fixed, animated or video);
- As there is a concentration on the use of AR at Secondary and Tertiary Education levels (97.96%), it would be useful to analyze more deeply in which curricula and years of these levels the AR systems are mostly used in the teaching of Chemistry, relating the applications to the topics of the disciplines;
- In a similar perspective, due to the reduced number of applications of the “Markerless” type of system (only three), it is possible to infer that this type is still in an initial process of use in the area of Chemistry, requiring further investigation related to its impact on the teaching and learning process;
- Information about the interventions' duration was not obtained in 67.35% of the studies, with the majority reporting periods up to 60 minutes. This characterizes a great difficulty in investigating the effects of AR in the development of long-term memory. No empirical studies have been found on how AR can effectively create long-term memories in students, but only a few theoretical perspectives. Longitudinal studies are necessary to develop new methodologies and improve the use of AR technology in Chemistry education;
- It seems clear that the potential of AR can be expanded to more diverse fields in future studies. Projects and implementations of AR systems applied in Chemistry educationcould involve different audiences, such as students with special needs, learners in the context of informal education, and the elderly.

Conclusion

This research aimed to identify how Augmented Reality has been used in the Chemistry teaching and learning processes. For this purpose, an analysis of articles indexed in the ACM Digital Library, IEEE Xplore Digital Library, ScienceDirect (Elsevier), Scopus, and Web of Science databases was carried out from 2011 to 2020. A total of 2926 studies were obtained in the first phase, reaching 49 accepted articles in the final phase, which is the set of primary studies evaluated. Results showed several trends, such as:

- Students at Secondary and Tertiary Education have been the most frequent target audience in the studies carried out (97.96%);
- The most frequently used type of platform has been Mobile (73.47%);
- The most frequently used type of AR system has been the Marker-based (89.80%);
- The most frequently followed research approach has been Quantitative (59.18%);
- The most frequently used instrument for data collection has been the Research Questionnaire (43.68%);
- The number of participants involved in the studies has been mostly in the range between 31 and 100 (42.86%);
- The most frequent duration of the instruction time has been up to 60 minutes (18.37%).

The results suggest that AR is increasingly being used in the process of teaching and learning in Chemistry, in an educational context in which students from Secondary and Tertiary Education levels are the vast majority. For this audience, different types of tools are designed and implemented as a beneficial resource.

Inherent to the growing number of publications in recent years (Figure 2), it was noticeable that the studies carried out addressed mostly quantitative research, using survey questionnaires as the main data collection instrument, with the predominance of experimental studies focusing on analyzing the effectiveness of AR in the educational process. However, although a large number of participants is expected in quantitative research, most of the experiments examined involved a number of participants in the range between 31 and 100 members. In addition, most studies did not report the duration of the experiments, and among those that did, there was a predominance of interventions with up to 60 minutes of duration.

This scenario allows us to confirm the idea that although AR has been present in the field of Chemistry for some time, in recent years there has been a greater number of works focusing on the understanding its real impact. Therefore, the predominance of a small number of participants and the experiments being carried out in a relatively short period of time may be due to the fact that these studies are still at an early stage.

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