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Opportunities and challenges of using immersive technologies to support students' spatial ability and 21st-century skills in K-12 education

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Abstract
Organic chemistry, also known as stereochemistry, is a subject considered to be notably complex for students to understand. Knowledge construction in stereochemistry might demand the ability to imagine or visualise the distribution of atoms. For students with insufficient spatial ability, this could be confusing. This study aimed to explore empirically students and teachers' experiences regarding the opportunities and challenges they encountered when using virtual reality (VR) and augmented reality (AR) technologies to teach and learn stereochemistry, as well as how these technologies might support students' spatial ability and 21st-century skills in K-12 education by participating in virtual lab environments. Using design-based research methods, an exploratory study based on the utilization of immersive technologies was designed and carried out with three groups in Grade 8. Two researchers observed the activities that were implemented, after which the participating students answered a qualitative survey about how these technologies and the specific teaching design might support their understanding of molecules in 3D space. The schoolteacher was interviewed afterwards, and she shared her motives and goals (e.g., what she sought to achieve) by using the technologies in her teaching. The results show that the students had a positive experience in their learning of chemistry through immersive realities, increased motivation to learn the subject, and their test results improved slightly. However, it is essential for a teacher to possess technological know-how regarding VR and AR to achieve the intended goals. The findings highlight the added value of these immersive technologies by enhancing students' learning processes and the central role of the teacher as a designer and technological leader of the group.

Keywords Spatial ability · Organic chemistry · Chemistry learning · Virtual reality · Augmented reality · 21st-century skills · K-12 education

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1 Introduction

Stereochemistry is a chemistry topic already present in comprehensive school (Swedish National Agency for Education, 2018). Its study comprises the spatial structure of atoms with respect to the three dimensions, which affect molecular properties. Stereochemistry is a major subject area for medicine and pharmacy because it delves into the use of various molecules in drugs, a pillar of the current health system. For several reasons (e.g., its capacity to bolster sustainable progress and medicine), chemistry has the potential to be a popular subject for students. However, the number of chemistry students at universities is shrinking (Broman et al., 2011). Learning stereochemistry demands a competent spatial ability to visualize the distribution of atoms; it has been claimed that "the acquisition of spatial skills is important for student success in chemistry" (Carlisle et al., 2015, p. 490). It is assumed that spatial ability can be developed through training, but requires appropriate methodologies (Carlisle et al., 2015; Wu & Shah, 2004). Newcombe et al. (2002) addressed the idea that spatial ability is malleable regardless of gender or previous spatial experience and that the effects of training with such materials can be long lasting. Their results are essential to the idea that all individuals might improve their spatial skills given appropriate practice or training and that superior ability is not a prerequisite for success.

Providing adequate teaching and exploring the available possibilities could be understood as a multilevel responsibility from teachers and administrators to researchers. The digital transformation in education opens many new ways of teaching and learning and, according to Kalolo (2019), "With this comes a responsibility to ensure that all related digital technologies are as contextually and culturally relevant as possible for all citizens. When this situation is properly addressed, such technologies are likely to have good future promise in education" (p. 351). That is, a critical approach to the technologies or methodologies available to support students' spatial ability must be behind the adoption of new methodologies for such learning and support any digital transformation in the matter. The digital transformation in education is understood here as an ongoing process of change towards the adoption of a wider array of technology in the classroom, mirroring the process happening in society. In line with Zizikova et al. (2023), we believe that "the process of digitalization is long-term and in this regard, digital literacy is an integral part of education in any field of knowledge" (p. 2), which characterizes a modern education system.

Daza Pérez et al. (2009) explored various scenarios in the chemistry subject area where digital technologies could be supportive for students. They affirmed that the use of information and communication technology allows students to integrate other forms of learning, improve the understanding of concepts that are difficult or impossible to observe with the naked eye, use representations to develop school projects with peers and teachers, and manipulate, for example, molecules in 3D or all kinds of substances in virtual laboratories. Due to their potential to display data in 3D, virtual reality (VR) and augmented reality (AR) have been considered means to support chemistry students in visualizing molecules in 3D and to help students increase their spatial ability (Mårell-Olsson & Broman, 2020; Sarıoglu & Girgin, 2020).

It is relevant to consider that the adoption of these technologies in teaching requires the involvement of teachers with the proper level of digital competence (Cabrero-Almenara et al., 2021). It is argued that a teacher's digital competence directly affects the use of technologies in the classroom (Antonietti et al., 2022), and hence teachers must be digitally competent to strengthen students' learning through digital technologies. However, teachers may or may not develop their digital competence during their teacher training (and afterwards), leading to different levels of digital use in the classroom depending on the teacher's education and beliefs (Olofsson et al., 2020).

Another challenge regarding the implementation of, for example, immersive technologies in comprehensive school is the lack of access to technologies in schools (Fransson et al., 2020), which leads to schools having a low capacity to exploit VR or AR and their educative potential.

More studies on immersive technologies in K-12 education are needed to explore the potential and the difficulties to be confronted (Fransson et al., 2020; Kavanagh et al., 2017). In line with this need, the aim of this design-based research study is to explore the opportunities and challenges students and teachers encounter when implementing and using VR and AR technologies in the classroom to support students' spatial ability and 21st-century skills (i.e., collaboration, critical reasoning, communication, solving complex problems, and being able to use and manage digital tools and devices). Hence, the use, more specifically, of VR and AR glasses for students' learning was expected to provide a different approach for students to visualize, assimilate, and better understand nonvisible and abstract spatial content. The aim was to understand, primarily from the students' perspective, the opportunities and challenges they experienced in using VR and AR technologies to support their understanding of, as in this example, the 3D representation of molecules. Furthermore, the purpose was also to investigate the participating teacher's motives and goals (i.e., what the teacher wanted to achieve) for the specific designed teaching activity in support of students' spatial ability and 21st-century skills in the study of chemistry.

Research questions:

1. What opportunities and challenges do students experience when using VR and AR technologies to support their learning and spatial ability and 21st-century skills?
2. What are the participating teacher's intentions (e.g., what the teacher wants to achieve) in using VR and AR technologies in teaching to support and train students' spatial ability and 21st-century skills?
3. What are the opportunities and challenges from a teacher's perspective?

2 Background

2.1 Supporting students' spatial ability

The unpopularity of chemistry among students (Broman et al., 2011) may be due to (a) students not understanding the concepts and elements on which the discipline is based (Trajano Raupp et al., 2020) and (b) students lacking the spatial skills necessary to understand the complexity of the spatial atomic distribution and its consequences (Carlisle et al., 2015; Tamayo & Cadavid, 2013). In chemistry, "Students learn molecular geometry, how to draw organic structures in a variety of formats, stereochemistry, and group theory. All these concepts require the involvement of spatial skills" (Harle & Towns, 2010). However, spatial skills are often underdeveloped and should not be taken for granted. Veurink and Sorby (2011) conducted a longitudinal study in which students who had taken a spatial ability course reported achieving better results on calculus, physics, and chemistry tests, although the improvement in scores in chemistry was "marginally significant". Furthermore, spatial ability is described as a necessary skill within the areas of science, technology, engineering, and mathematics. Despite these results, described as "marginally significant" in the area of chemistry, it could be that spatial ability, as Trajano Raupp et al. (2020) affirmed, is not enough if the fundamental concepts of the subject are not learned. In line with this idea, neither element is exclusive, but rather they work together.

However, educators and researchers have explored spatial ability and students' development of it by means of training activities and by using different types of technologies. Copolo and Hounshell (1995) presented three ways for students to develop their spatial ability: (a) intellectual exercises based on a 2D environment (tests), (b) ball-and-stick models, and (c) 3D computer reconstructions, including VR and AR. In their study, they compared using 3D computer reconstructions with the commonly used so-called ball-and-stick models. They found that both physical and computational models could offer benefits as an effective tool for teaching molecular structures and isomers. However, they also suggested that manually manipulating physical models might distract students from focusing on the image of molecules, whereas using computer models allowed students to concentrate on the molecular representations (Copolo & Hounshell, 1995).

2.2 Supporting students' 21st-century skills

It is not only necessary to support students' spatial ability in teaching chemistry, as researchers have stressed, but also to support their overall 21st-century skills as future competences they need for living and working in a digitized society. Such skills as collaboration, critical reasoning, communication, solving complex problems, and being able to use and manage digital tools and devices are often referred to as *21st-century skills*. However, there is a lack of clarity as to what the concept of 21st-century skills really means, and according to Dede (2010), the same terminology is used to mean different things. Further, Dede states that organizations such as, for example, Partnership for 21st-Century Skills, the North Central Regional Education Laboratory, Metri Group, OECD, the National Leadership Council for Liberal Education, and America's Promise have developed their own frameworks for supporting students' 21st-century skills concerning the content and processes for teachers and for students' education. Hence, in a digitized society, where the advancement of digital technologies changes quickly, students need skills such as being able to think creatively, collaborate, solve complex problems, and make full use of the opportunities that digitalization offers to a greater extent than before. For example, Jahnke (2015) stressed the importance of changing learning approaches towards what she called a "learning expedition," where the students are able to make independent decisions during their learning process and teaching activities are designed to support self-reflection (e.g., part of supporting 21st-century skills). In line with Jahnke (2015), Jonassen et al. (2002) stressed the importance of using technology to support students' learning and these different skills. They argued that when students are allowed to use technology for complex problem-solving tasks and information-retrieving purposes, it may benefit their learning processes. They further argued for student-centred approaches for achieving what they termed "meaningful learning" (Jonassen et al., 2002).

2.3 Using VR and AR in teaching and learning

The regular use of VR and AR technologies for educational purposes in schools is still quite uncommon, and teachers must be digitally competent and confident enough to adopt new teaching approaches (Mårell-Olsson & Broman, 2020). Studies have shown that the use of immersive technologies in teaching also has an effect on students' motivation and engagement in their learning processes (Di Serio et al., 2013; Hung et al., 2017; Kaufmann, 2002). For example, Qin et al. (2021) studied VR spaces designed to promote concentration, and they described VR environments as "pure information spaces: malleable learning environments where the objects of study are highlighted, and distractions are downplayed" (p. 521). Häfner et al. (2018) described how diverse opportunities can be enhanced by using immersive technologies, and they categorized the opportunities and conveniences of using VR in education into seven categories: (a) enhanced student motivation through the use of technology; (b) enhanced communication as a result of language barriers being overcome through the use of VR and evaluation of a learner's performance being more substantive and objective when using computer-supported evaluation processes; (c) improved understanding of complex phenomenon that can be visualized or repeatedly trained; (d) flexibility and adaptability to individual needs (e.g., visualized processes can be slowed down or additional information easily added); (e) safety and health aspects, where dangerous tasks are simulated instead of experienced in reality and these scenarios can be trained in advance without the pressure of the danger of a real environment; (f) the environmental friendliness of simulations because the use of VR for training leads to a reduction in material consumption; and (g) time and cost effectiveness for certain kinds of training and a shorter preparation and debriefing time (Häfner et al., 2018, p. 103).

However, Garzón et al. (2019) emphasized the importance of developing immersive technologies because their potential for learning is high and the use of immersive technologies in education has only just begun. Further, in their systematic review and meta-analysis of using AR in educational settings, conducted between 2012 and 2018, they found that AR, for example, has a medium effect on learning, and the most explicit benefits concern learning gains and motivation. For example, students in Hung et al. (2017) stated that it was hard to move between a virtual 3D representation and the 2D representation of 3D figures, and the researchers found that the students liked the use of an AR graphic book more than the use of a regular picture book and physical 3D figures. Kaufmann (2002) found that the students rated learning about geometry in 3D using AR versus a PC-based computer-aided design programme significantly higher (i.e., more satisfying); however, the usability of the AR programme was rated lower than the PC alternative. DiSerio et al. (2013) compared an AR teaching approach with a slide-based approach in a visual arts class, and their results showed that student motivation was significantly higher with the AR teaching approach compared to the slide-based approach. Furthermore, Echeverría et al. (2016) identified a difference in motivation between male and female students, where the male students explored the technology beyond the designated tasks more and therefore learned more about the technology itself than the subject. The female students tended to complete the tasks but did not further investigate the technology. In Mårell-Olsson and Broman's (2020) study of the use of AR technology in teaching organic chemistry to support university students' spatial ability and 21st-century skills, they did not find any gender differences in the use of the AR technology between male and female students, but they found that integrating immersive technologies such as AR technology and changing traditional teaching designs is overall a rather complex process. Furthermore, they argued that both students and teachers' preparedness for this appears to be low. Moreover, they stated that integrating, for example, AR technology into teaching design is a very complex process for teachers to handle. Teachers must combine competences such as technological, pedagogical, and content knowledge (see the TPACK model by Koehler et al., 2013) to find what Mårell-Olsson (2019) termed a "pedagogical balance" when designing a teaching activity in which students can use advanced technology to enhance their spatial ability, for example, in stereochemistry.

However, it could be important for today's contemporary education to explore further the use of VR and AR technologies in teaching to support students' understanding of molecules' 3D representation in chemistry (i.e., spatial ability) and to support their 21st-century skills within this context as well. Based on this background, we raised questions about whether it is possible to design a teaching activity for compulsory school where the students can train 21st-century skills while simultaneously using VR and AR technology to support their spatial ability by visualizing the 3D representation of molecules in the classroom.

Hence, this paper reports on a design-based research study investigating a teaching activity specifically designed to develop students' 21st-century skills and spatial ability. More specifically, the study aimed to empirically investigate the opportunities and challenges students experienced when using VR and AR technologies, in addition to being able to collaborate and reason critically by solving complex problems in groups to support their understanding in chemistry. Furthermore, the purpose was also to investigate the participating teacher's motives and goals (i.e., what the teacher wanted to achieve) and experiences (e.g., perceived opportunities and challenges) with the designed teaching activity.

3 Study context and participants

This study was conducted with three school classes in Year 8 (i.e., 15 year olds) in Sweden. The three school classes shared the same teacher and belonged to the same school. It was the schoolteacher who showed interest in testing these immersive technologies to help and support her students in visualizing molecules in 3D to help them to "think spatially". The teacher contacted one of the researchers she knew was doing research within this area and asked for advice. The researcher had conducted studies using immersive technologies as educational tools before and saw an opportunity to study these technologies applied to spatial ability in comprehensive education. The teacher agreed to participate in a design-based exploratory research study. The study was conducted during the spring term of 2022. In total, one schoolteacher and about 90 students participated in the designed activity in the classroom, and 42 of the students answered a survey afterwards, after agreeing to participate in the study. In addition, the teacher was interviewed afterwards. Hence, the designed teaching activity was tested three times with three school classes in Grade 8.

4 Methodology and methods

A qualitative approach was employed to explore and understand the opportunities and challenges associated with implementing and using immersive technologies, such as VR and AR, in a specific teaching setting. The goal was to support students in enhancing their spatial ability regarding the understanding of molecules' 3D representation in stereochemistry, while also supporting their 21st-century skills. Consequently, a study inspired by design-based research methods was conducted, which is suitable for both research and designing teaching for technology-enhanced learning environments (Design-Based Research Collective, 2003; Wang & Hannafin, 2005). Design-based research methods offer an iterative, flexible, and collaborative approach that combines empirical educational research with theory-driven design of learning environments with an aim to improve educational practices and develop context-specific design principles (Design-Based Research Collective, 2003). This approach provides an effective and collaborative framework for exploring the potential of immersive technologies, such as VR and AR, in a specific teaching setting (i.e., chemistry teaching) to support students in increasing their spatial ability. By working closely with teachers and students, researchers can develop, test, and refine interventions that address specific educational challenges and contribute to the broader knowledge base on teaching with immersive technologies such as VR and AR in education.

Design-based research methods involve several steps, such as (a) identifying the problem, (b) collaborating with stakeholders, (c) designing the intervention, (d) implementing and testing the intervention, (e) analysing the data, (f) refining the intervention, and (g) documenting and sharing findings (Wang & Hannafin, 2005). In this study, we began by identifying the problem. The schoolteacher had an idea about what she wanted to achieve using VR and AR technologies in teaching chemistry (e.g., increasing students' spatial ability and understanding of molecules' 3D representation in stereochemistry). Subsequently, the classroom activity was designed in collaboration with the schoolteacher (i.e., collaborating with stakeholders and designing the intervention) and then tested three times with her Grade 8 classes (i.e., implementing and testing the intervention, analysing the observation data, and refining the intervention). The researchers were present during each test of the activities in the classroom, providing technical support and clarifying instructions when necessary. Our presence enabled us to observe the students and teacher's reactions in practice during every test and analyse the data after each test to refine the activity for the next round. After each classroom test, we discussed the outcomes of the observations with the teacher and determined the necessary changes for the next iteration. We observed and took notes during each activity (i.e., test) while the students performed the tasks in the classroom.

For instance, observation notes from the first test indicated that some students were initially nervous. After the first test, the researchers and the schoolteacher decided that one of the researchers would provide technical support at the beginning of the second test. As a conclusion from the first test, it was determined that some technical training was necessary and should be included in the final prototype (i.e., designed learning activity). Furthermore, the software crashed multiple times during the first test, which is a common issue when dealing with immersive technologies (Fransson et al., 2020). In this case, the teacher needed a quick solution while the activity was ongoing with students in the classroom. For the second and third tests, she learned how to redesign the virtual learning environment rapidly in the software used in the study.

4.1 Procedure

The designed classroom activity was inspired by a gamification perspective and consisted of three activities at different stations in the classroom. One activity was based on VR technology (i.e., using VR glasses), and another on AR technology (i.e., using AR glasses). The content at all the stations was decided and designed by the teacher, although the VR and AR activities (i.e., the VR and AR stations) were designed together with the researchers due to their complexity. Five activities were going on at the same time in the classroom, which were done in groups of 3 to 5 students in each group. The students collaborated in each activity (e.g., station) and had up to 8 min in each for solving the given problem/task. The groups earned points depending on how they succeeded in each station. One reason for using a station design for the activity was the limited number of VR and AR devices available.

4.2 Development of activities related to immersive technologies

The station based on AR used a pair of Microsoft HoloLens 1 glasses (i.e., AR glasses). The design of the activity was limited by the availability of only one pair of glasses. A virtual 3D molecule was designed using Google SketchUp software.

Through the glasses, the students could see a virtual 3D model of a nicotine molecule (see Fig. 1), and it was overlapped to the real world (i.e., students using the glasses could see in parallel both a virtual object and the real world). They could walk around the molecule and see it from different perspectives and interact with it, even walk through it. Once they had seen the molecule, they had to find out which molecule it was by counting the atoms and identifying the types of atoms involved. They had computers at that station which they could use as they wished.

In contrast to the AR station, the VR station had five Oculus Quest 2 VR headsets at hand. It allowed five students to share a virtual environment at the same time (see Figs. 2a and b). The activity used a VR platform called Nanome, which is a collaborative virtual reality tool for molecular design. Teachers and students can naturally interact with any molecular structure together in an immersive virtual environment.

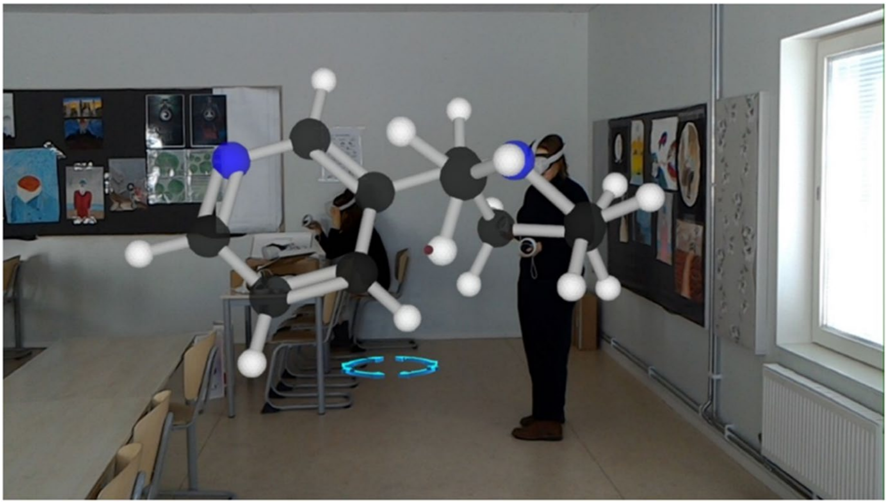
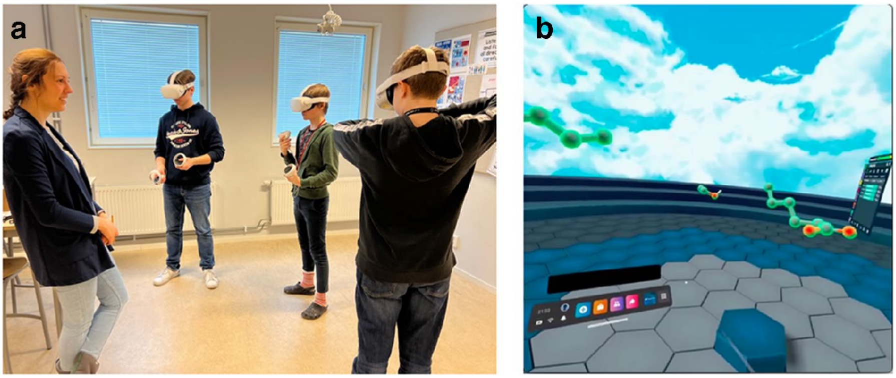


Fig. 1 The nicotine molecule projected by the AR glasses (i.e., Microsoft HoloLens 1)



Figs. 2 Illustrate three students using the VR glasses sharing the same virtual environment in Nanome

This platform is recommended for higher education, but it was possible to use it in comprehensive school by using only part of its potential. The teacher designed four molecules and uploaded them to the platform. Students using the headsets could access Nanome, and with the right password provided in advance, they could access a virtual room at the same time and see each other's avatars and the molecules the teacher had prepared for the activity. The assignment for the students in this activity was to find out what types of molecules were on display. They were invited to discuss it and collaborate while in the virtual environment and, in collaboration, decide what types of molecules were projected, write them down on paper, and give it to the teacher, who awarded points depending on whether the answers were correct.

4.3 Software used for the activities

As mentioned above, the Nanome software (see Fig. 2b) was used with the VR glasses, and it has advanced features for both education and research. The activity's design for the presented study was grounded on (a) self-design of molecules which can be uploaded and put on display for others to view; (b) a virtual platform for displaying the molecules that allows avatars to move the molecules around, manipulate them, and zoom in or out; and (c) a communication tool that allows users to communicate remotely.

4.4 Data collection

The empirical material was collected through observations, and we wrote field notes focusing on the students' actions and words while testing and on discussions with them during the activities. For example, the discussions with them could be to clarify what they meant by a specific expression (e.g., both verbal, facial, and bodily expression) while testing or what they meant by something they said. As stated above, this aided in the design process and provided instant on-site feedback.

A postsurvey with 42 of the participating students was also conducted to collect their individual experiences on the opportunities and challenges they perceived during the activity regarding both the use of the VR and AR technologies for learning and how the projecting of 3D molecules could support their understanding and learning of stereochemistry. The survey was voluntary, and nearly 50% of the participants agreed to respond to the survey about what had occurred during the lesson. The survey focused on the following areas of the experience: (a) their experience of using the VR and AR technology in the classroom, (b) their thoughts about opportunities and challenges related to VR and AR in education, (c) the possibilities of cooperation within virtual worlds, and (d) their ideas about learning stereochemistry through VR and AR.

A postinterview was also conducted with the participating teacher, focusing on her motive and goal for the designed activity (e.g., what she wanted to achieve with the activity) and her experiences with regard to the outcomes and lessons learned. It was essential to understand the students' experiences concerning opportunities and challenges related to the use of immersive technologies and their benefits in school in relation to the teacher's expressed intentions for the activity (i.e., motive and goal) and the station-based designed activity for the students to perform in the classroom (i.e., operationalization). The teacher interview was held on Zoom and lasted for 1 h. The interview touched upon planning and implementation of the activities in the classroom and opportunities and challenges of immersive realities in education.

5 Theoretical framework

The theoretical framework for exploring and understanding the students' experiences and their view of the opportunities and challenges (e.g., outcomes), in relation to what the teacher wanted to achieve with this specific activity, is based on Leontiev's (1986) activity theory. Activity theory and its key concepts of motive, goals, actions, and operationalization enable exploration of a context and its chain of actions, for example, in this study, from a teaching idea (e.g., motive and goals; what to achieve) to the operationalization in the classroom (i.e., the teaching activity), as well as the tools and materials used and social relations. Activity theory also enables exploration of the interplay between these aspects and how they affect actions in different situations. When using activity theory as a theoretical framework, the focus is not only on a perspective, for example, the individual student's actions or the teacher's actions, but also on the group's actions within the specific activity system (e.g., in this study, the teaching situation in the classroom). Moreover, in activity theory, it is important to study the role that an artefact or tool plays within the activity system (Nardi, 1996); in this study, the artefacts were VR and AR technologies in teaching and learning. Leontiev (1986) saw an activity as a system including elements of specific motive, goals, actions and operations. For example, teachers carry out operations in the classroom (i.e., teaching), and these operations can be, for example, procedures or practical examples of a topic or different routines, and these are related to the preconditions within the school organization. The routines, procedures, or practical examples carried out in the classroom comprise combined actions. However, the actions are related to the motive and the goals a teacher is trying to pursue (see Fig. 3). In this study, teaching in the classroom with the designed activity using VR and AR technologies is regarded and analysed as one activity system.

In this study, activity theory is used as an overall theoretical framework framing the study at different levels concerning, for example, the motive and goals to explore the teacher's intentions regarding what to achieve in the teaching activity and actions taken to reach the expressed motives and goals. The concept of operationalization concerns the operation of the designed activity (i.e., the station-based activity in the classroom). In summary, this study was inspired by and includes aspects of design-based research methods and could be described as being of an exploratory nature.

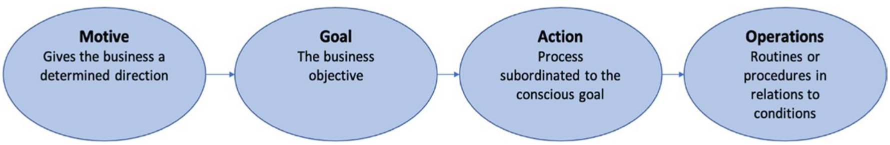


Fig. 3 Key concept within an activity system (Leontiev, 1986)

5.1 The process of analysis

To construct an understanding and meaning of the empirical material and identify key themes and an emerging pattern, we used thematic analysis (Ely, 1991). This type of analysis process in qualitative research could be described as a process for encoding qualitative information. Hence, thematic analysis can assist researchers in the search for insight. Boyatzis (1998) described this process as including two perspectives concerning both “seeing” and “seeing as”. Creswell (2013) explained the process of “seeing as” in the process of analysing qualitative data as searching for repetitive patterns of significance (i.e., meaning). Hence, the analysis process of both “seeing” and “seeing as” for constructing meaning includes several readings of the empirical material in an iterative process to identify emerging patterns and then construct themes. The iterative analysis process included various steps: (a) reduction of data (coding), (b) categorizing the data (categorization), (c) constructing and presenting the data (thematization), and (d) summarising the data (conclusions and verification). According to Ely (1991), a theme can be described as a definition of utterances or expressions that all informants express in response to a question or a single statement of an opinion that has a great emotional significance. In this study, the data from the student survey and the teacher interview were first coded into categories within the focus areas for the survey and the interview, and then the themes were constructed within each category. The data include what the students expressed as their experiences of opportunities and challenges in using immersive technologies in the classroom and how the teaching was organized and implemented (i.e., actions and operationalization) and the teacher’s description of what she wanted to achieve with the designed activity (i.e., motives and goals).

The themes constructed from the empirical material, as presented in the next section of findings, were thus derived from and formed during several iterative steps in the analysis process. In Section 6 below, the quotations should not be regarded as evidence but as illustrations of the constructed themes in the analysis process. All quotations are translations to English from the original surveys in Swedish.

6 Findings

6.1 Findings from the student survey

The findings are presented in four themes. The first theme concerns the students’ experiences related to the use of the immersive technologies in the activities. The second theme illustrates their thoughts about learning supported by immersive technologies. The third theme regards their reflections on immersive technologies as means to boost collaboration in learning. The fourth theme concerns the role of immersive technologies as support for developing students’ spatial ability and understanding of abstract content in chemistry.

6.1.1 Students' experiences regarding the technologies used

The theme of students' experiences regarding the technologies is presented in three subthemes: (a) immersive technologies as a fun, dynamic, and new experience; (b) a remarkable sense of reality; and (c) difficulties in using the technology or understanding the activities.

6.1.2 Immersive technologies as a fun, dynamic, and new experience

The students identified the immersive technologies used as enjoyment and movement of the body. In this context, they appreciated the technologies because they perceived them as something new, which motivated them to perform the activity because it differed from their normal classroom routine; it took them out of their normal patterns and allowed them to move around instead of sitting still in their chairs. Most of them called it a positive experience because it added diversity to the behaviours they usually experienced during lesson hours, and it allowed them to experience technologies they were not able to try in another way. We have selected a few quotations from the survey illustrating the students' experiences in this matter. Examples of answers are as follow:

> Example 1 "It was fun and exciting because you are curious. You could move around while everything else was moving with you".
> Example 2 "I think it was fun, exciting, and interesting because I had never tried AR glasses before and had only tried VR glasses a few times before the activity".
> Example 3 "It broke the normal pattern of what we do during classes, and it was fun to try something new. . The activity was motivating and engaging in a way that made you feel expectant, interested, and you felt that it was fun and exciting to try that kind of technology".

6.1.3 A remarkable sense of reality

The students also commented on the sense of reality within the virtual environments. They enjoyed the 3D experience and compared it with their previous experiences visualizing content on paper. Examples of answers are as follow:

> Example 1 "It was also good to see molecules in 3D because, before, we have only been able to see their structure on paper".
> Example 2 "I thought it was cool to be able to see it as a structure that stood still and you could walk around it to see all the sides".
> Example 3 "It was like it was really there, even though you knew no one else could see it and others walked through it while you yourself almost thought it was there; it was super fun."

6.1.4 Difficulties in using the technology or understanding the activities

Some students' comments referred to difficulties in using the technology or understanding the activities, malfunctioning of the technology, inadequate space due to poor lighting that hindered viewing, or existing dangers due to the possibility of moving around in a room full of people and furniture. Examples of answers are as follow:

Example 1 "I think that for the VR glasses, you needed a larger space where you are not afraid of colliding with someone or something. In the AR glasses, it was a little difficult to see certain colours. I think it was because of the light in the room".
Example 2 "The hard part was starting to learn the controls in VR because you first had to try and find out how to do it. . When you used VR glasses, it was difficult with the controls, how to 'walk', etc. I kind of really wanted to walk".
Example 3 "It was a bit difficult to control with your hands, and it was easy to walk into a wall in real life or something. You can easily collide with someone or something. It was also a bit difficult to hear one's peers given the other students in the class".

One student mentioned feeling nauseated during the activity: "It was fun, but when you were tired, the glasses made you feel sick". This affected her experience negatively. This is a consequence that can happen when using immersive technologies. Only one of the students alluded to the inconvenience of the technology chosen for the activities by stating, "VR and AR are not developed enough. I still believe that advanced technology in computing would improve students skills more than VR and AR would. It feels difficult to use with minimal results. It was hard to see the molecules."

6.2 Students' thoughts about learning using immersive technologies

Comments from the students referring to learning and education using immersive technologies can be clustered in six subthemes: (a) 3D visualizations as a valuable assistant for learning, (b) learning by playing, (c) motivation, (d) an embodied experience, (e) distance education, and (f) the use of immersive technologies as counterproductive for learning.

6.2.1 3D visualizations as a valuable assistant for learning

Many of the students acknowledged the potential of 3D visualizations and indicated that they could be a valuable assistant for learning processes. In the quotes below, the participants argue that immersive technologies could facilitate concentration and understanding to a greater extent because the object of content becomes visible and it is possible to look at a virtual object (e.g., molecules) at different scales and from different angles, which the students appreciated. Examples of student answers are as follow:

Example 1 “I see opportunities to see perspective and scale represented right in front of my eyes. More concentration teaches more. Better ways to display information”.
Example 2 “I think you can learn faster and more if you can see them in real life”.
Example 3 “I think they can be good when you really understand what you are talking about because you can see them, and it is good to see things from different perspectives and forms in a different way”.

6.2.2 Learning by playing

The students established connections between playing and learning due to the perceived fun involved, which made them willing to perform. The Nanome software is not a video game, but it has components that can be identified as such; for example, the embodied experience provided, the use of avatars, the chance to cooperate, and the possibility of using the software to design the activity as a competition. Examples of student answers:

Example 1 “You were very committed and wanted to solve the task and, for example, win”.
Example 2 “It can be more fun to learn in VR and it can feel like a video game, which can make people who like to play want to participate in the teaching more”.

6.2.3 Motivation

The students’ answers also indicated increased curiosity. This curiosity could be interpreted as being technology-oriented; for example, they expressed that they wanted to explore the technology more because it was new for them (i.e., they had not tried it earlier). They also expressed curiosity regarding the subject. For example, they wanted to explore the content of the subject more than earlier because they found it interesting due to technological mediation. They expressed that both these paths led them to engage more, and they could focus more on the content for the activity.

Example 1 “It was motivating because you were curious, and when you are, you want to know things”.
Example 2 “It’s hard to explain, but there was such a feeling that you just wanted to keep exploring more and more. You learn better because you are curious and get more motivation to focus + work well because it is fun to use VR and AR glasses”.

Example 3 “People who aren’t that motivated in school might want to learn more if they can try stuff like that. I think it would interest more people and make them want to participate in learning because they find it exciting and want to try the technology”.

6.2.4 An embodied experience

It was significant that the students’ described their experiences as a form of “modern” learning and that they valued embodied, active, and dynamic learning centred on physical experimentation with the subject. One student expressed, “It was new, and it was a more modern and physical way to study. You had to stand up and move around and talk in groups”.

6.2.5 Distance education

The students referred to several opportunities for distance learning in the future in their answers, which could be interpreted as being due to the use of the technology.

Example 1 “I think it could open up several opportunities in the future if you could teach in that way because then people who are not present can participate through VR or AR”.
Example 2 “Students who are ill, for example, can take part in lessons, and concepts that are difficult to understand can be understood more easily with the help of VR and AR glasses”.

6.2.6 The use of immersive technologies as counterproductive for learning

Some students also expressed nondidactical experiences and stated that the use of the technologies could be counterproductive, distracting or a hindrance to their learning. Examples of student answers are as follow:

Example 1 “The reason why I think the VR glasses made our teamwork less effective is because I felt too distracted by the new experience of the VR to be useful for my team”.
Example 2 “They [the molecules] wouldn’t have been difficult normally, but the use of VR and AR glasses made it more difficult to figure them out”.

6.3 Immersive technologies and collaboration

The interpretation of the results suggests that the technologies used were suitable for promoting collaborative work. Almost all students expressed having participated in good collaboration within their groups. The quotations below illustrate the most generalized emotions regarding collaboration:

Example 1 "I thought the collaboration worked well; we all had our own ideas about how we could solve the task, and it gave us more probability to complete the task. Everyone did well; everyone contributed with their knowledge".
Example 2 "We all used our abilities, and everyone could be with me and help, some more than others, but no one was left out".
Example 3 "It worked great, and we could all put in our own thoughts and ideas to get the right answer. We were all good at different things, so everyone could participate in all the activities".
Example 4 "It was very fun and something you don't do that often at all, but you learned a lot and became closer with your classmates when you worked in groups".

Apparently, not all groups worked equally well. Some of the students said that participation in their group was unbalanced, which could be interpreted as a negative experience of teamwork, and some students expressed the concern that it could prevent some of the students from learning. The quotations below address differences in group participation that were perceived as bad for those students with less knowledge regarding the content or the use of the technologies.

Example 1 "I mostly carried the whole team, so there wasn't a lot of collaboration because I like NS [i.e., natural sciences] more than the rest, I'd say".
Example 2 "Bad, one person did everything during the AR station and one took notes, but otherwise, we just stood and watched. At the VR station, I was completely lost and didn't understand the task before. The other two in my group basically did everything, while I couldn't do anything because I'm not good with technology".

6.4 The role of immersive technologies as support for developing students' spatial ability and understanding of abstract content in chemistry

The students described visualizations as supportive in understanding organic chemistry for different reasons. For example, the content was recognized as real, and it provided different perspectives and more accurate visualization of the molecules. Examples of answers are as follow:

Example 1 "I think being able to see the molecule was great for better understanding of the subject we were working with. The VR glasses and AR glasses gave me a greater understanding of how the molecules and atoms were put together".
Example 2 "Right now, with the VR and AR technology we have in everyday life, the strongest possibility within NS [i.e., natural sciences] is probably to see the chemical structure of molecules, as I said".

Example 3 “Because you can see them in 3D, it was easier to understand the structure. The bonds and structure, etc., are easier to understand if you can see them. It’s like you can see them and how they work and are built”.

The experiences students expressed about immersive technologies as an aide to spatially understanding the molecules were also forwarded. This mainly concerned contrasting the VR and AR technology with the ball-and-stick models they had been using in the chemistry class. Some students reflected on both systems and their capacities to support understanding of stereochemistry. In the following quotations, it is possible to read how some students did not see any added value when using immersive technologies:

Example 1 “I think one understood better how the molecules looked in 3D form, but you could also see that with the 3D models in plastic [i.e., the ball-and-stick models]”.
Example 2 “Well, we had access to the molecular building blocks [i.e., ball-and-stick models], so it’s not that overwhelming”.

Among students who considered that VR and AR did not help them more than the book or even a simple piece of paper without referring to the ball-and-stick models, one student said, “I thought it was cool, but it didn’t help much. You have already seen what the molecules look like, for example, in the book or in a film”. Some students stated that they could see these technologies as an efficient means of content revision and mentioned a need for previous knowledge to take advantage of technology use. One student expressed it as follows:

“You understand better how the bindings are and stuff like that, but it didn’t help much more than what I already knew. Actually, it hasn’t helped very much, because I already knew to some extent how the molecules looked in 3D with the help of other school materials. If anything, it helped to remember or rehearse things that we have gone through”.

6.5 Findings from the teacher’s interview

In this last part of the Section 6, we present the interview of the participating teacher in two themes: (a) planning and implementation of the activities in the classroom and (b) opportunities and challenges of using immersive technologies in teaching.

6.5.1 Planning and implementation of the activities in the classroom

In the interview, the teacher stated that she wanted to engage and motivate her students to a greater extent. She said that she thought it was “an interesting way to get the kids engaged” because it was “something different and something exciting”. She declared that she had heard of these technologies and their potential, and therefore, she contacted one of the researchers (see “Study Context and Participants”). She mentioned that she saw making such contact as essential to being able to develop an activity using immersive technologies for various reasons: Her school lacks digital technology beyond computers or tablets and she lacked the technological skills to be able to conduct the activity by herself. This following statement illustrates her feelings towards collaboration with other institutions that can support her in developing better teaching: “I think anytime I’m given any opportunity from a university or from anyone who knows a lot more about the topic than me, I will take it”.

She also referred to her personal education as poorly focused on teachers’ digital competence. She described a short module where she and her classmates.

> played around with that a little bit to see how we could use it in science. And they talked more about, like, in the human body, and then, I think it was in – so, like, going to visit different places in the world using Google Cardboard. But it wasn’t in a lot of detail, or, you know, with an academic background. . “What’s the research behind this?” or anything. It’s just, like, “Here’s a fun thing,” right?

However, she said in the interview that she wanted to explore these technologies pedagogically because she had seen some students have difficulties. She described this as follows: “Picturing molecules and then naming them is quite hard for them. So, I thought that could be just another way to help them do that”. Students picturing molecules and naming them concerns their spatial ability, and this could be interpreted as what she was trying to develop through the activity presented in this study.

She also said that not having used the software before caused her to invest extra time trying the software at home, which gave her a feeling of insecurity. According to the observation notes, despite this quite heavy training at home, the software failed at the first test, and she had to solve the problems on site. As a result, the first student group trying the technology perceived it as more challenging than the other two, when the teacher had learned how to solve the technical problems that occurred. For example, in the first test, the molecules she had prepared in advance in the virtual room suddenly disappeared, and she had to build them once again in the classroom.

Despite technical problems that occurred during the tests, she considered the implementation to be a success: “Yeah, I think it was really good. I’m so happy you guys came in to do it with us. Thank you for letting me do this”.

The reason behind this opinion, according to the teacher, is that the students did not want to leave the classroom when the lesson was over. According to the observation notes, the students seemed very motivated and they expressed that they perceived the activity as fun and engaging with big smiles on their faces. The teacher said in the interview that the students, weeks after the activity was held, still remembered it and what they did, so she could refer to it later and create what she referred to as “knowledge associations”.

6.5.2 Opportunities and challenges of using immersive technologies in teaching

The teacher described the use of immersive technologies in teaching as complementary tools for students’ learning. She expressed it as follows: “I thought it could be just another way to help them do that, aside from, you know, they’ve been building with their, like, molecule kits and things like that". This could be interpreted as her view of these technologies as tools to add diversity to her teaching. She also addressed the possibility of adapting content to different levels of complexity, which she perceived as very useful: "Because they've never used virtual reality before, for the most part". For that reason, and because of the level of knowledge in the eighth grade, she decided to use only some of the capabilities of the software for the VR glasses: "Looking at molecules and being able to name them was kind of the simplest we could – could do". However, she saw further opportunities for using this specific technology in chemistry and other subjects concerning more advanced functions and complex tools that involve reasoning and creativity (i.e., 21st-century skills).

Furthermore, lack of competence, already addressed when she was describing her opinion about the implementation, was perceived as the main challenge. Technical problems that might occur in the classroom are also perceived as a difficulty, but they can be overcome if a teacher has the ability to solve them in the classroom or minimize them beforehand.

7 Discussion

This study has explored and identified opportunities and challenges in using immersive technologies as additional learning tools within the context of stereochemistry with three specific school groups in eighth grade. The findings illustrate opportunities for teaching and learning when implementing immersive technologies. Among the opportunities are, for example, motivation, diversity, enjoyment, movement, sense of reality, better understanding, good opportunities to collaborate with others, and greater opportunities for distance learning. The participating students said that their understanding of the spatial distribution of molecules was expanded thanks to large-scale, realistic visualizations and an individual, personalized perspective. Difficulties also arose, such as trouble with understanding the technology or the activity, among the main concerns.

Students' experiences of immersive technologies as useful tools to reinforce content construction or enhance distance learning are an important viewpoint in line with current research. Researchers have studied the opportunities that immersive technologies could bring in experiencing virtual chemistry labs and have compared the students' perspective of learning in a physical lab to the experience in a virtual lab (Qin et al., 2021). No significant differences were reported, so virtual labs were identified as an effective space with high potential for remote education (Qin et al., 2021). This could be seen as an important milestone for e-learning and education embedded in a digital transformation, but also for students who cannot attend school for health or other reasons.

The participants in this study recognized many opportunities that could be improved by implementing immersive technologies in learning. This could be related to Häfner et al. (2018), who categorized the advantages of using immersive technologies in the classroom. These categories were also recognized when analysing the student survey content: (a) increased motivation, (b) enhanced communication, (c) better understanding of complex content, and (d) flexibility or adaptability to individuals.

In line with Hollett et al. (2020), participants experienced friction when using VR and AR headsets. Hollett et al. described “handheld frictions” as the frustration experienced by the participants during the first minutes of the activity, the time they reported feeling unsure about how to act. Participants in their study stated that although they had received good instructions, the first minutes were chaotic: Participants could not move and they pressed buttons without reference. After some time trying, they found out how the tool worked. This experience mirrors the feeling of some of the students participating in this study, who expressed some troubles when trying to move around in the VR environment that made the experience for them not entirely satisfactory, or at least improvable. The discomfort lasted some minutes, and after a while, they felt better. Another challenge Hollett et al. described was body friction, or the feeling of insecurity when the body moves within the virtual world. The participants in our study experienced clear uncertainty when visualizing molecules with AR in a scenario that brought together the real world and the virtual. They said it felt wrong to walk through the molecule, even if they understood and knew it was projected virtually. It was with the support of the researchers that they dared to do it. This reflects a misunderstanding of the virtual object, which could be perceived as provoking uncertainty and fear.

We argue that these situations, which Hollett et al. aptly labelled *friction*, could be seen as included in students’ digital competence, and we also argue that more regular contact with immersive technologies could help them feel more secure and take better advantage of its potential by preparing students for a future where immersive technologies may be much more commonly used (Fransson et al., 2020).

Overall, considering the nervousness some students showed when dealing with the immersive technologies and the confusion it created, observed by the researchers during the tests in the classroom, adequate technical support is needed. In addition to technical support, emotional support is also needed to push students gently to at least give the technology a try despite their demonstrated negative feelings or fear. One student did not want to participate, and further conversations with the teacher made us believe the reason for this could be a fear of looking bad with the glasses on or being perceived as ridiculous.

Córica (2020) analysed teachers’ resistance to changing their teaching and said that uncertainty due to lack of knowledge and fear of failure is among the major reasons for this type of resistance. Fransson et al. (2020) pointed out the lack of previous knowledge as a challenge that is difficult to overcome. However, the findings in this study in relation to activity theory could be described as the motive of the teacher identified as an intention to support spatial ability and 21st-century skills among her students and to motivate and engage them to a greater extent in the content (i.e., stereochemistry). This can be considered a complex process due to the fact that different kinds of knowledge, such as content knowledge, pedagogical knowledge, and technological knowledge (Koehler et al., 2013), are needed. The teacher’s expressed motive and goals for the specific activity were based on using immersive technologies in teaching, due to their capacity for visualizing abstract content or phenomena, to engage her students more in their learning process. However, the teacher did not perceive that she had the technological knowledge required or, in other words, the capacity to develop this activity by herself, but in collaboration with one of the researchers with knowledge about using VR and AR technologies in chemistry teaching, everything became a reality because the researcher had the capacity, both knowledge and access to artefacts (headsets). In this respect, we can assert that the university–school relationship was a determinant. The teacher used her pedagogical knowledge and skills to design the actions to be taken, each of them motive- and goal-oriented. These actions consisted of visualizing the molecules, collaboration between students to solve various tasks related to the 3D images, and analysis of the 3D molecules and their structure.

Overall, this could be interpreted as the expressed motive and goals for the activity (Leontiev, 1986) directing these actions (e.g., operations in the classroom), and these operations were intended to reach the motive and goals for the performed activity, where the virtual visualization of the molecules (i.e., supporting spatial ability) and the reasoning and collaboration to solve a complex problem together in student groups (i.e., supporting 21st-century skills) could help and support students' understanding of and learning in organic chemistry.

We argue that these practices (using VR and AR for stereochemistry content visualization and complex problem-solving with peers) foreshadow a possible future of chemistry education where virtual labs could take centre stage, simulating professional spaces to enhance motivation and understanding. The educational system should engage in a process of change to overcome challenges encountered, such as developing teachers' digital competence, to reach a future where education through virtual and immersive experiences is widespread. We believe that this utopian scenario could be a new normality in education, and it would constitute a significant part of modernized education, making it more inclusive, democratic, and focused on diversity. It would involve exploring various teaching methods to accommodate different learning styles and employing diverse methodologies to help all students achieve better understanding and competency development. This new normality is expected to be shaped by the ongoing digital transformation, accelerated by the pandemic but previously rooted in our education system (see, e.g., how in prepandemic times new disciplines [e.g., digital history or digital humanities] had already emerged in the context of the digital transformation), because the professional future will likely be mostly digital, so will be communication and other practices. In line with these professional and societal changes, national and international organisations such as the Swedish National Agency for Education (2018) or the OECD (2018) have pointed out the need for an education for a digital future.

We also argue that as the teacher and the students in this study observed, new practices in education would affect not only stereochemistry education but other themes and subjects as well. We are particularly interested in understanding how immersive learning can affect the learning processes of abstract and intangible knowledge, while considering both the positive and negative aspects to create well-designed activities or prototypes for educational improvement. It is not only in chemistry that immersive technologies could support the development of students' abilities and their understanding of complex and abstract phenomenon. The use of VR technologies and virtual learning environments has been beneficial, for example, to obtaining multiple perspectives by offering different views of the same phenomena or of causation by helping students to understand that tridimensionality is important for the function of molecules. These concepts, namely multiple perspectives and causation, are essential in other subjects such as history, but the construction of the virtual content is and should follow different premises regarding the particularities involved in each theme and goal. There are risks and potentials in the use of immersive environments, and we argue that these must be studied from a subject-oriented perspective, so further analysis under these premises is needed.

Following this subject-oriented perspective and after a proper process of design, virtual labs could be extended to various subjects, which would extend opportunities to diversify learning. Is it too early to implement VR and AR in education? It might be, but we must begin to think about it, design for it, test it, and reflect on it. This reflection should be aimed at affecting decision-making processes in teaching and the design of teaching and learning tools, so that this new normality can be grounded in scientific knowledge and prove efficient. In line with Kalolo (2019) and linking with the multilevel responsibility needed to succeed in the digital transformation of education we started with (see introduction), "The sooner the governments embark on a digital transformation, the more technology literate individuals are likely to be in making the best of this opportunity" (p. 357).

8 Conclusions and implications for practice

In summary, it can be concluded that the use of immersive technologies in teaching brings several opportunities to K-12 stereochemistry education. Students might acquire motivation and curiosity, which is directly linked to better learning. The use of these technologies in teaching might be good for developing teamwork skills, helping in the division of labour and in the development of problem-solving attitudes. The use of these technologies seems to be effective in supporting the understanding of complex and abstract knowledge, such as the spatial structure of molecules. However, the problems that arose in our study when developing an immersive activity in the classroom prevented participants from using and taking advantage of all the potential it could bring. Furthermore, it also remains to be seen whether the sense of novelty is what triggers the motivation; this could be affected if the students had VR and AR technologies at hand, as they have the textbook.

Despite a certain shortage of technology use according to some of the student comments, they in turn argued that this technology could be supportive for students with diagnosed concentration disorders (cf. Mårell-Olsson et al., 2019) or bad performance at school. It is possible that the acquisition of several sets to support these students could be beneficial. However, further research is needed.

Concerning the teacher's perspective on using immersive technologies in teaching, it could be seen as a complex process where several knowledge domains and skills are needed which, in turn, need to be combined (see Koehler et al., 2013) to reach what Mårell-Olsson (2019) termed a "pedagogical balance". Integrating immersive technologies in teaching, specifically concerning the process of designing this type of teaching practice in education, is hence a rather complex process for which the preparedness of both teachers and students appears to be low (cf. Koehler et al., 2013; Mårell-Olsson, 2019). This complexity involves designing activities that correspond to the actual operations in the classroom that in turn correspond to the intended motive and goals for what the students should learn (i.e., what to achieve). For the teacher, this concerns being able to possess different skills and combine, for example, subject content and pedagogical and technological knowledge (Koehler et al., 2013) in the teaching design as well as to combine these areas (i.e., different knowledge domains or TPACK; Koehler et al., 2013) with the teachers' creativity and problem-solving skills (e.g., 21st-century skills) when designing classroom activities (i.e., operations; Leontiev, 1986). Further, it is also essential for a teacher to possess expertise regarding immersive technologies such as VR and AR (Mårell-Olsson & Broman, 2020) to achieve the intended motive and goals for the teaching activity (i.e., operations) and the added value these immersive technologies offer by controlling the operations of the actions in the classroom (Leontiev, 1986).

However, in this case, it is not only the teacher who must have certain technological knowledge of the use of VR and AR glasses. The students also must be trained to use this type of technology. For example, an activity could be developed whereby the students could focus on just handling the devices properly. Thus, it could be wise, as Mårell-Olsson and Broman (2020) suggested, to conduct activities beforehand where the focus is merely on handling the devices (i.e., technological use). This could, in turn, help the students to concentrate on the content to be learned and the teaching activity (e.g., content knowledge and pedagogical methods).

This study has explored and illustrated the use of VR and AR technologies in teaching with a focus on supporting students' spatial ability and 21st-century skills in teaching organic chemistry. Furthermore, students and teachers' experiences concerning perceived opportunities and challenges have been the focus of the study. This study could also be seen as an effort to give an empirical example and illustrate a teaching design with a specific focus on trying not only to support spatial ability in chemistry but also at the same time to support students' overall 21st-century skills as future competences they need for living and working in a digitized society (e.g., the new normal).

9 Limitations and future studies

A methodological concern with this study is the selection of participants. Including more school classes and students as participants and more participating teachers would result in more data and, perhaps, richer nuances. However, time constraints and access to teachers expressing their ideas for developing their teaching with immersive technologies in chemistry made further data collection impossible. Another methodological concern is the survey construction and the data analysis. During the analysis, it was noticed that answers regarding Themes 2 and 3 were sometimes blurred (i.e., students described the activity as motivating and engaging, which are two elements related to both enjoyment and learning). For the answers to be coded as Theme 2, the content had to relate directly to learning. It was considered the right way to code it because it is safer to know when they were referring to the learning experience and not just to their entertainment. A third methodological concern is the chosen theoretical framework of activity theory and the qualitative approach. Naturally, different analysis and different results could have been obtained if a more theory-driven approach had been chosen. However, the combination of a qualitative approach with activity theory as a theoretical framework (Leontiev, 1986), a design-based research approach (Wang & Hannafin, 2005) and thematic analysis (Ely, 1991) were regarded as beneficial for obtaining an increased understanding of the opportunities and challenges students and teachers encounter when implementing VR and AR technologies in teaching with the specific motive and goals of supporting students' spatial ability in chemistry and at the same time supporting their 21st-century skills and for us researchers to answer the research questions.

A recommendation for future research is not only to expand the range of participants but also to conduct more design-based research in collaboration with schoolteachers regarding other school subjects, such as history or religion. This could enable a combination of specialized advanced technological expertise with the use of, for example, immersive technologies in teaching to combine such domains as content and pedagogical knowledge (Koehler et al., 2013) to achieve teachers' intentions for their teaching (i.e., motives and goals; Leontiev, 1986) and make it possible to conduct teaching activities with immersive technologies, as presented in this study, in the classroom (e.g., by controlling the operations of the actions; Leontiev, 1986). This could in turn further broaden the understanding of students' learning processes and how to support their 21st-century skills.

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