Virtual Reality and Zoom in combination to visualise chemical structures and develop students' spatial ability during the Corona pandemic

Karolina Broman, Erik Chorell, and Michael Holmboe, *Umeå university*

***Abstract*—In chemistry education, students need to develop their competence to visualise chemical structures and reaction mechanisms, for example, to be able to predict how chemical compounds react. As a chemistry or biotechnology engineering student, this competence needs to be practiced. In our project, students have since 2018 used Virtual Reality (VR) to learn to "see" chemistry, and to move between 2D and 3D representations, i.e., spatial ability or spatial thinking. During the Corona pandemic, several teaching challenges have had to be handled, and Zoom has become the most common teaching and communication platform in Sweden. When combining VR with Zoom, students had a possibility to develop their spatial ability even though distance teaching, something described in this paper. The combination of VR and Zoom is explored further for future teaching implications even post-Covid.**

***Index Terms*—Visualisation, Organic chemistry, Virtual Reality, Zoom**

I. Introduction

Chemical structures and reactions are always three-dimensional (3D), even though represented in books and on the screen in two dimensions (2D), often as so-called Lewis structures. The competence to visualise chemistry in 3D in one's own head, is an important competence to master when learning chemistry, and through this visualisation competence, chemists and engineers can predict how and why chemical compounds react. Chemistry experts are used to apply this spatial thinking or spatial ability, i.e., visualisation through the move between 2D and 3D, without realising it, whereas novices as students often find spatial ability challenging [1]. Spatial ability is a competence that is possible to develop and enrich through practice [2, 3], and in our project described in this paper, university chemistry students had the opportunity to apply Virtual Reality (VR) during workshops and tutorials, to visualise organic molecular structures.

Several recent studies on Virtual Reality have explored affective aspects as interest and motivation, cognitive aspects as visualisation and spatial thinking, or a combination of aspects. In an American study [4], students found the use of VR interesting, motivating and exciting. Furthermore, an Australian project [5] followed university chemistry students' visualisation of molecular interactions between enzymes and substrates, where the conceptual understanding increased by the use of VR, moreover, students also collaborated in a meaningful way. In general, digitalisation and digital tools are important aspects to explore further within education to design relevant applications, and McKnight and colleagues [6] have stated important roles for technology to improve teaching and thereby, hopefully increase learning. Examples of roles for digital tools and techniques as VR are; making teaching more efficient, giving broader learning resources, connecting people, where the last example will be explicitly explored here.

Small molecular structures can be visualised through plastic ball-and-stick models (see figure 1), whereas larger structures as biomolecules are too complicated to build in analogue formats. Therefore, visualisation of more complex chemical representations benefits from being presented digitally. In an American project [7], large protein structures are represented through WebVR, that is, VR representations accessible on the Internet, to help students develop their spatial ability. An evident advantage with the WebVR technology is the availability, and today the technology is "mature" enough to be implemented in chemistry education [8]. A normal smartphone can easily be combined with relatively inexpensive VR headsets/goggles (e.g., Google Cardboard), and can thereby be used to visualise a 3D projection of abstract concepts as atoms, molecules, and bonds [9]. More advanced VR goggles (e.g., Oculus Rift or Oculus Quest), can with the use of hand controls, also make students more active. In this project, both simple VR goggles and more advanced ones have been applied to explore students' visualisation of chemistry (see figure 2).

Karolina Broman is with the Department of Science and Mathematics Education, Umeå university, Sweden (corresponding author e-mail: Karolina.broman@umu.se).

Erik Chorell is with the Department of Chemistry, Umeå university, Sweden (e-mail: erik.chorell@umu.se).

Michael Holmboe is with the Department of Chemistry, Umeå university, Sweden (e-mail: Michael.holmboe@umu.se).

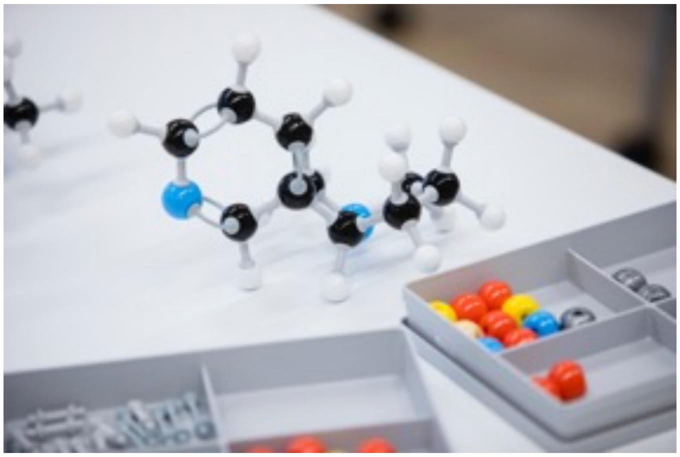

Fig. 1. Plastic ball-and-stick models are commonly used in chemistry education to visualise structures.

Fig. 2. Visualisation through Virtual Reality, using Oculus Quest goggles and Nanome software to explore protein structures.

In higher education, VR can develop immersive learning and facilitate both visualisation of 3D structures, but VR has also been explored in the field of practical laboratory work, especially when it comes to dangerous experiments that might be difficult to do due to risk exposure [10]. Through the use of 360° videos where students can interact, VR makes it possible for students not only to see something predetermined by the teacher, but also to be active learners. VR laboratory simulations are, according to results from Danish research [11], a possible solution to some of the challenges of chemistry education, for example, as a way to raise students' potential low interest, and also as a way to rise student' expectations on how chemistry can be perceived, as a modern science subject.

Jiménez [12] summarises eight reasons to apply VR environments for students, that is, to provide learners with (1) methods of visualisation for detailed observations, (2) more time to proceed through an experience, (3) an environment where physical disabilities may not be an impediment, (4) a medium that transcends language barriers, (5) an exciting and challenging environment in 3D in which they can interact and create their own 3D worlds, (6) a way to learn about historical places and events, (7) a platform to learn independently, and (8) a more enjoyable way to learn, among other advantages. These reasons, perhaps not the sixth one, are considered in our project and will be presented in relation to the empirical data as a theoretical framework.

One fundamental aspect of spatial thinking is the possibility to rotate the chemical representations. Rotation is a spatial factor that experienced chemists do instinctively, but an aspect students need to practice and develop over time [13]. By the use of VR, students can be given the opportunity to see how molecular representations look from different angles when rotated. Rotation is therefore the spatial factor that will be explored further here; other spatial factors are further discussed in depth by Buckley and colleagues [14]. A well-known rotation test from psychology, i.e., the Purdue Visualization of Rotations Test [15], is applied in this study, to get a non-chemistry variable to compare with.

II. Methodology

This design-based research project [16, 17], is an ongoing project since 2018, where university chemistry teachers and a chemistry education researcher have collaborated. Design-based research being situated in a real educational context, has an apparent advantage since it emanates from a collaboration between research and practice, where experiences from both the university chemistry teachers and the chemistry education researcher are equally important. Cobb and colleagues [18] describe design studies in educational contexts as "test-beds for innovation", being pragmatic and theoretical, prospective and reflective, with an interventionist and iterative nature, and with a final aim to develop theories, not only describe best practice. Since the project is a cyclic process, experiences from year 1 have been elaborated further in the following cycles, i.e., year 2, 3, and 4. Interventions were designed and developed further over the years, in 2018, only one VR workshop was implemented, whereas in 2021, students met several workshops in different chemistry courses.

The close participation between university chemistry teachers and the chemistry education researcher was an important parameter in this design-based research project. Through the use of the individuals' various competencies, all aspects of the TPACK model [19] (see figure 3), co-operated towards innovation. Within the project group, the aspects of content knowledge (CK), pedagogical knowledge (PK) and technological knowledge (TK) were fulfilled. During the summer of 2021, a teaching assistant (i.e., amanuens) was hired to explore possible options to enhance new learning opportunities through VR. Results from this new intervention will be discussed in later publications.

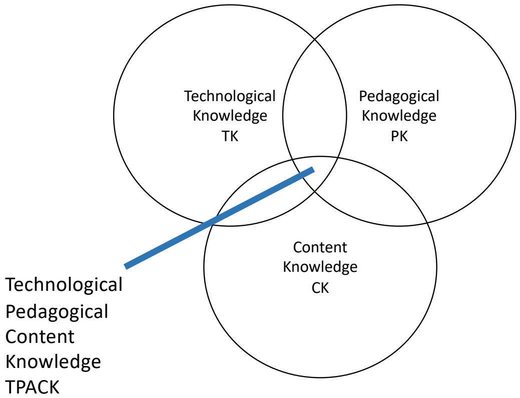

Fig. 3. The TPACK model [19] describes how teachers' and researchers' different competencies are valuable to combine when collaborating in, for example, design-based projects.

Fig. 5. Students used the simple VR goggles with smartphones inserted, where the Zoom app on the phone could be used to see the structures in 3D. Due to Corona restrictions, the students had to sit with distance.

At chemistry courses within the Biotechnology engineering programme and the Bachelor programme in life science, the students were given the opportunity to apply WebVR and meet 3D visualisations of chemical structures in different workshops. During 2018-2019, teachers and students worked close to each other in organic chemistry workshops, presented at a previous engineering conference [20]. Due to the Corona teaching restrictions during the years 2020-2021, the teachers could not be closer than 1,5-2 metres to the students, which made it difficult to help students to become active VR users. Therefore, the methodology of the project had to be adjusted to Corona restrictions. Instead, one teacher applied the VR application, Oculus Rift combined with Nanome software, and streamed the visualisation over Zoom, the teaching platform used by most universities in Sweden. The other teacher and the students, used simple VR goggles with their smartphones to see the 3D projected molecules, and the teacher orally explained what was represented on the screen (see figures 4 and 5).

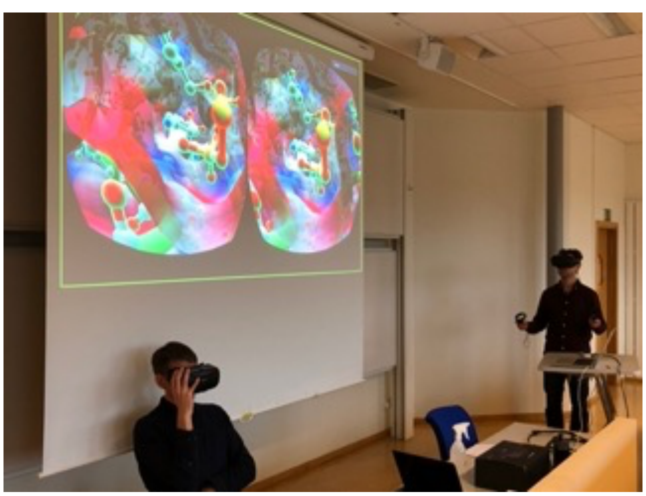

Fig. 4. Two university chemistry teachers collaborated to visualise complex chemical structures, when one teacher (right) used the more advanced VR goggles Oculus Quest, and streamed the visualisation through Zoom, whereas the other teacher (left) used the more simple VR goggles (i.e., similar as the students use in Figure 5), and synchronously explained to the student group what was shown.

When doing design-based research, mixed-method research is requested to get a thorough and deep picture of a project [16]. Therefore, we collected both qualitative and quantitative empirical data. Students responded to a pre-test survey with both open and closed questions, where they were asked about their technological and content opinion related to both chemistry and VR, and were also given a visualisation rotation test (i.e., Purdue Visualization of Rotation Test, for one exemplary task, see figure 6) [15]. After the VR workshops, post-surveys explored how students perceived the use of VR to visualise chemistry. The chemistry education researcher also participated at the workshops and collected observational data. Finally, post-interviews were done with students to scrutinise and further explore data from the surveys to get a more comprehensive picture. In this paper, focus will be on the results from 2020 and 2021 (i.e., workshops during the Corona pandemic), but will be discussed in relation to results from previous years with VR workshops. Simple statistics from the quantitative data is presented, together with some first observation and interview results, analysed with content analysis [21]. The theoretical frameworks of situational interest [22] and value creation [23] framed the analysis and structured the categorisation process. Standard ethical procedures [24, 25] were followed in this project. More elaborated results will be presented in an up-coming paper.

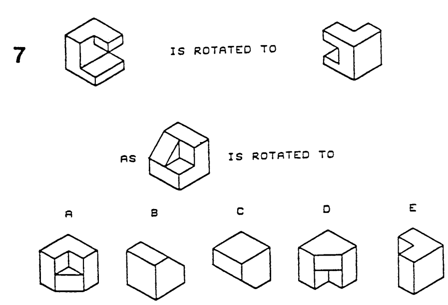

Fig. 6. One exemplary task from the Purdue Vizualisation of Rotation Test [15] that the students solved in the pre-survey, to explore the spatial factor of rotation.

III. RESULTS AND DISCUSSION

Over time, from 2018 until 2021, the use of VR was in general perceived valuable and interesting, and students claimed to develop their spatial ability. Students appreciated to see the structures in 3D, and they found the different workshops worthwhile. Nearly all students wrote in the surveys that VR was helpful to visualise the molecules, and that this gave a deeper understanding of chemistry. During the whole project (four years, 2018-2021), results from 157 students' pre- and post-surveys, indicate that chemistry in general is perceived interesting (mean 5.2 on a 6-grade Likert scale), still quite challenging to learn. Almost all students were also positive when it comes to modern technological releases, claiming to appreciate to try new digital (educational) tools, even though most students never tried VR for educational purposes prior to the workshops. Thereby, students had high expectations when joining the VR workshops. After the workshops, students also claimed that the VR workshops were highly valuable (mean 5.1 on a 6-grade Likert scale).

The empirical data from the Purdue Visualization of Rotation Test [15] shows that students in general solved the rotation tasks with a satisfying result, however, they also often stated that they were unsure with their responses, that the tasks were found difficult to solve and that they were insecure of their responses. In the interviews, these results were explored further, and students emphasised that it was easier with the tasks from the Purdue Visualization of Rotation Test (see figure 6), since the forms were quite simple, whereas the 3D molecules were more complex and uncommon to the students. One exemplary quote shows how organic chemistry students perceived the rotation of the molecules: *When we solved the tasks before the workshop* (i.e., the Purdue Vizualisation of Rotation Test)*, I recognised them from IQ tests that I have seen before, I really think they are fun to solve, even though tricky. But with the molecules, it was challenging to see which atoms that were going into or out of the plane. During stereochemistry lessons, the teacher talked about rotation of the molecules and optical activity.* It was apparent that teachers often discuss a "plane", perhaps not being specific of what is intended. In stereochemistry, mirror images are used as an analogue for chiral molecules, and the "plane" is something two-dimensional whereas molecules are three-dimensional. The importance of communication, and that teachers are explicit in their talk, was apparent from both the observations and interviews.

During the first years of the project, less complex structures were studied during a course in Organic chemistry, for example small haloalkanes as Bromo-Chloro-Iodomethane (see figure 7), or medical drugs as Ibuprofen. In 2020 and 2021, the software of Nanome was applied in the course of Biological chemistry, with a possibility to visualise larger and more complex molecules as proteins, DNA and also large inorganic structures (see figures 2, 4, and 8). From the post-survey, students were asked to state advantages and challenges with VR when experiencing molecular structures in 3D. The most common advantage was the possibility to understand the relationship between 2D and 3D of molecular structures, i.e., spatial ability, and that students appreciated to visualise chemical representations by the use of VR. Several students expressed that Nanome was a "powerful tool" to comprehend how matter interacts. They also looked forward to future possibilities to try the advanced VR goggles (i.e., Oculus Quest), and thereby be more active users. Challenges stated by the students were mostly related to the technology, for example, lag time, blurry images due to bad Internet connection, and that students realised that software often needs to be updated. It is therefore important to have a stable technological competence among the teachers, and to realise that students often enjoy new teaching practices. However, a few students felt dizzy or sick after using the simple VR-goggles for a longer time. Therefore, the teachers also presented the visualisations on the large screen in the classroom, even though this only gave a 2D experience.

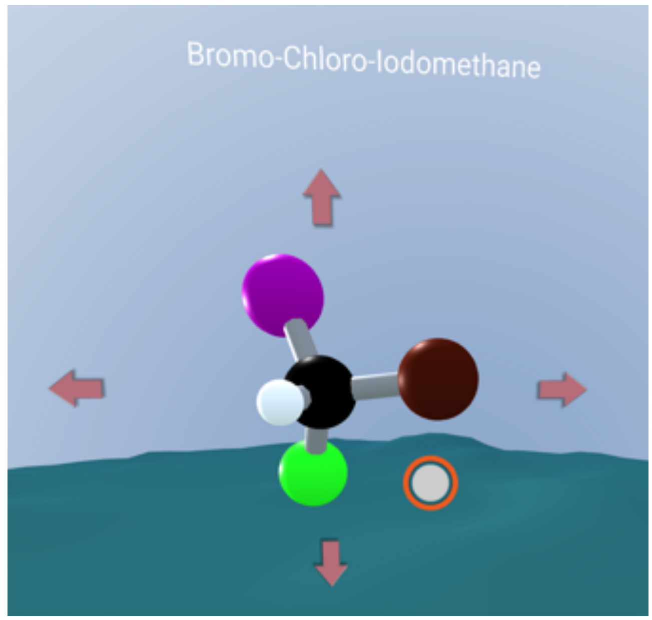

Fig. 7. Simple organic structures as Bromo-Chloro-Iodomethane were presented during the first years of the project to visualise molecules in 3D.

Fig. 8. Large and complex biomolecules visualised through the software Nanome, https://nanome.ai.

The more complex structures, for example shown in figures 4 and 8, were aesthetically appealing according to the students. During the observations, students expressed both fascination and excitement to "see" chemistry in this way. The colours of the atoms in the molecules, i.e., the CPK model from Linus Pauling and Robert Koltun [26], were sometimes a challenge, since there were forms describing single atoms, but on the same time, forms describing larger structures as proteins and their structural levels. For example, the blue arrows in figure 2, are not the same as the blue nitrogen atoms, something some students expressed to be confusing. The teachers therefore had to be explicit and observant about different structural levels in their communication.

For the engineering students, the use of new technological tools was in itself also stated to be valuable. During the interviews, several engineering students emphasised the importance to be updated, not only on content, but also on the teaching procedures. Students realised that tools as VR might be used in their future working life, and this made the students more engaged to realise advantages, and possible disadvantages to visualise chemistry through Virtual Reality.

The combination of VR and Zoom made it possible for the teachers to teach without, or at least with a very low, risk of Covid-19 to spread. The simple VR goggles students used, see figure 5, are made of plastic material and can easily be cleaned with alcohol. The more advanced goggles (i.e., Oculus Quest, see figure 8), are more difficult to share between people due to risk to spread viruses, which made it valuable to be able to stream the visualisation from Oculus Quest through Zoom to students' smartphones, possible to apply in the simple VR goggles. Since Zoom has an app for smartphones, streaming was possible. One teacher, or the teaching assistant that worked in the summer of 2021 to develop VR teaching practices, used the Oculus Quest and the visualisation of the chemical structures was streamed through Zoom to the students' smartphones. The smartphones with the Zoom app were then placed into the simple VR goggles and thereby the students could see the same things the teacher or teaching assistant decided to show. Obviously, this will in the future, post-Covid, be replaced by the students using the advanced VR goggles themselves, making it possible for them to become active learners.

IV. CONCLUSIONS AND IMPLICATIONS

During the Corona pandemic, digital teaching has been inevitable due to the restrictions to meet at campus. University teachers have therefore been obliged to develop their TPACK competence [19], and in general, the technological competence has probably improved much faster as teachers has been forced to teach digitally. However, even before Corona, we have shown that digitalisation of teaching is effective [27]. Therefore, we realise that the implementation of VR in chemistry education will be relevant also post-Covid. The advantages to combine analogue plastic ball-and-stick models with digital visualisation tools, as VR, is evident, and we therefore claim that the combination of a state-of-the-art software as Nanome, with visualisation tools as Oculus Quest, is a feasible way to increase students' learning and interest in chemistry. The students' wish to be more active and use the advanced goggles will hopefully be easier post-Covid. Moreover, it is important to update teaching practices and show students modern ways to represent chemistry, especially for engineering students that probably will apply several different digital tools and technologies in their future working life.

In our project, several of the reasons to apply VR for learning opportunities stated by Jiménez [12] have been obvious to our students, for example, VR being exciting and enjoyable. It is evident that VR is a promising visualisation tool, with both exciting, enjoying and challenging settings where students can interact and be creative. The aspect of creativity in chemistry is an area that has become more important in educational research, and the use of VR with Nanome is an up-and-coming way to foster students for their future working life to see chemistry in a new, aesthetic and fascinating way. Last, but not least, the importance of teachers' conscious communication with students can never be emphasised enough. As an expert (i.e., teacher), it is sometimes easy to forget to be explicit and perhaps also too obvious when talking to novices (i.e., students). Explicit and intentional instructions are fundamental for teachers to communicate with students in learning situations if the aim is in-depth learning.

V. FINAL COMMENTS

For more information, see https://www.umu.se/en/feature/vr-glasses-help-students-visualize-molecules-/ and https://www.umu.se/en/news/teaching-assistants-help-in-education---and-develop-personally_10893745/

VI. REFERENCES

[1] M. Harle and M. Towns, "A Review of Spatial Ability Literature, Its Connection to Chemistry, and Implications for Instruction," *Journal of Chemical Education,* vol. 88, no. 3, pp. 351-360, 2011.

[2] A. Bongers, B. Beauvoir, N. Streja, G. Northoff, and A. B. Flynn, "Building mental models of a reaction mechanism: the influence of static and animated representations, prior knowledge, and spatial ability," *Chemistry Education Research and Practice,* vol. 21, no. 2, pp. 496-512, 2020.

[3] R. Kozma and J. Russel, "Modelling students becoming chemists: Developing representational competence," in *Visualizations in science education*, J. K. Gilbert Ed. Dordrecht: Springer, 2005, ch. 7, pp. 121-146.

[4] J. Parong and R. E. Mayer, "Learning Science in Immersive Virtual Reality," *Journal of Educational Psychology,* vol. 110, no. 6, pp. 785-797, 2018.

[5] M. Won, M. Mocerino, K.-S. Tang, D. F. Treagust, and R. Tasker, "Interactive immersive virtual reality to enhance students' visualisation of complex molecules," in *Research and Practice in Chemistry Education*, M. Schultz, S. Schmid, and G. A. Lawrie Eds. Singapore: Springer, 2019, pp. 51-64.

[6] K. McKnight, K. O'Malley, R. Ruzic, M. Kelly Horsley, J. J. Franey, and K. Bassett, "Teaching in a Digital Age: How Educators Use Technology to Improve Student Learning," *Journal of Research on Technology in Education,* vol. 48, no. 3, pp. 194-211, 2016.

[7] K. C. Cassidy, J. Sefčík, Y. Raghav, A. Chang, and J. D. Durrant, "ProteinVR: Web-based molecular visualization in virtual reality,"

PLOS Computational Biology, vol. 16, no. 3, p. e1007747, 2020, doi: 10.1371/journal.pcbi.1007747.

[8] B. Ferrell and J. Barbera, "Analysis of students' self-efficacy, interest and effort beliefs in general chemistry," *Chemistry Education Research and Practice,* vol. 16, pp. 318-337, 2016.

[9] B. I. Edwards, K. S. Bielawski, R. Prada, and A. D. Cheok, "Haptic virtual reality and immersive learning for enhanced organic chemistry instruction," *Virtual Reality,* vol. 23, no. 4, pp. 363-373, 2019.

[10] B. Marks and J. Thomas, "Adoption of virtual reality technology in higher education: An evaluation of five teaching semesters in a purpose-designed laboratory," *Education and Information Technologies,* 2021, doi: 10.1007/s10639-021-10653-6.

[11] G. Makransky, G. B. Petersen, and S. Klingenberg, "Can an immersive virtual reality simulation increase students' interest and career aspirations in science?," *British Journal of Educational Technology,* vol. 51, no. 6, pp. 2079-2097, 2020.

[12] Z. A. Jimènez, "Teaching and Learning Chemistry via Augmented and Immersive Virtual Reality," in *Technology Integration in Chemistry Education and Research (TICER)*, T. Gupta and R. E. Belford Eds.: American Chemical Society, 2019, ch. 3, pp. 31-52.

[13] M. Stieff, "Mental rotation and diagrammatic reasoning in science," *Learning and Instruction,* vol. 17, no. 2, pp. 219-234, 2007.

[14] J. Buckley, N. Seery, and D. Canty, "A Heuristic Framework of Spatial Ability: a Review and Synthesis of Spatial Factor Literature to Support its Translation into STEM Education," *Educational Psychological Review,* vol. 30, no. 3, pp. 947-972, 2018.

[15] G. M. Bodner and R. B. Guay, "The Purdue Visualization of Rotations Test," *The Chemical Educator,* vol. 2, no. 4, pp. 1-17, 1997.

[16] T. Anderson and J. Shattuck, "Design-Based Research: A Decade of Progress in Education Research?," *Educational Researcher,* vol. 41, no. 1, pp. 16-25, 2012.

[17] F. Wang and M. J. Hannafin, "Design-Based Research and Technology-Enhanced Learning Environments," *Educational Technology Research and Development,* vol. 53, no. 4, pp. 5-23, 2005.

[18] P. Cobb, J. Confrey, A. diSessa, R. Lehrer, and L. Schauble, "Design Experiments in Educational Research," *Educational Researcher,* vol. 32, no. 1, pp. 9-13, 2003.

[19] M. C. Herring, M. J. Koehler, and P. Mishram, *Handbook of Technological Pedagogical Content Knowledge (TPACK) for Educators*. New York: Routledge, 2016.

[20] K. Broman *et al.*, "Spatial Ability in Organic Chemistry – Can Virtual and Augmented Reality be Valuable?," in *7:e Utvecklingskonferensen för Sveriges ingenjörsutbildningar*, Luleå, L. Pettersson and K. Bolldén, Eds., 2019, pp. 143-145. Available: http://ltu.diva-portal.org/smash/get/diva2:1446954/FULLTEXT01.pdf.

[21] L. Cohen, L. Manion, and K. Morrison, *Research Methods in Education*, 8th ed. Abingdon: Routledge, 2017.

[22] K. A. Renninger, S. Hidi, and A. Krapp, *The role of interest in learning and development*. Hillsdale, NJ: Erlbaum, 1992.

[23] E. Wenger, B. Trayner, and M. de Laat, "Promoting and assessing value creation in communities and networks: a conceptual framework," Ruud de Moor Centre, Open University, Heerlen, The Netherlands, 2011.

[24] M. Denscombe, *Ground Rules for Social Research: Guidelines for Good Practice*, 6th ed. Maidenhead: Open University Press, 2017.

[25] Swedish Research Council, "Good Research Practice," Swedish Research Council, Stockholm, 2017, vol. VR1710.

[26] R. B. Corey and L. Pauling, "Molecular Models of Amino Acids, Peptides, and Proteins," *Review of Scientific Instruments,* vol. 24, no. 8, pp. 621-627, 1953.

[27] S. Bernholt, K. Broman, S. Siebert, and I. Parchmann, "Digitising Teaching and Learning – Additional Perspectives for Chemistry Education," *Israel Journal of Chemistry,* vol. 59, no. 6-7, pp. 554-564, 2019.