

Features of Immersive Virtual Reality to Support Meaningful Chemistry Education

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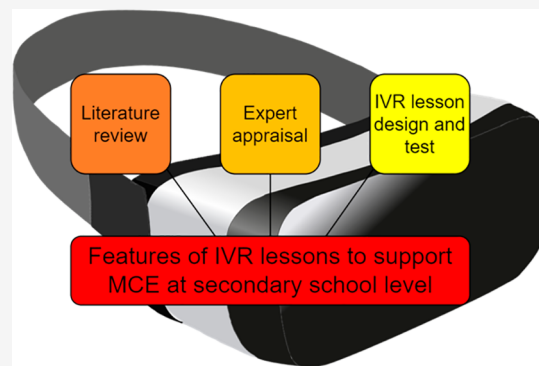
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ABSTRACT: One way of triggering students' interest in chemistry is making chemistry education more meaningful. Four characteristics of meaningful chemistry education (MCE) were identified in projects that involved a redesign of curriculum materials: daily life context, the need-to-know principle, students' input, and the macro–micro connection. Chemistry education has struggled with the implementation of meaningful learning. A possible solution might be the use of immersive virtual reality (IVR) in chemistry classrooms, a promising tool to support students' meaningful learning. IVR can be described as a computer simulation that provides an interactive simulated virtual environment, while the user wears a head mounted display and can experience immersion and presence in a virtual environment. The aim of this study was to explore features of IVR to support MCE at a secondary school level. A systematic literature search was done, experts were consulted, and animation- and 360°-IVR lessons were designed and tested in classrooms. Features that could support MCE found in both animation-IVR and 360°-IVR were: the application of the characteristics of MCE, the necessity of a storyboard, difficulties in realizing interactive visualization, and positive student experiences. These features can be used to design future IVR lessons to support MCE. Features needing careful consideration since they are different for 360°-IVR and animation-IVR are the need for a professional designer, the degree of interactivity, and classroom use with all students at the same time.

KEYWORDS: Secondary Education, Meaningful Chemistry Education, Characteristics of Meaningful Chemistry Education, Immersive Virtual Reality, Animation-IVR, 360°-IVR, IVR Features



INTRODUCTION

Students' interest in choosing chemistry in upper secondary education can be limited because they are not inspired by chemistry education in the way it is taught. They find concepts abstract, difficult to understand, and they struggle to visualize chemical concepts like molecular models.⁶² Students have difficulties seeing the relevance of learning chemistry, because it is often taught as combinations of isolated facts and not connected to their daily lives.^{11,17,48}

Meaningful chemistry education (MCE) is likely to stimulate students' interest in chemistry and inspire them to continue chemistry in their studies. Chemistry education can potentially provide students with important explanations of our ever-changing world.³⁷ It is said to be crucial for a population to understand the natural world, make decisions in daily life, and participate in debates of scientific issues that affect society in today's world filled with technology.^{9,36} Projects such as Salters (UK), ChemCom (USA), Chemie im Kontext (Germany), and PLON (The Netherlands) aimed to reform chemistry curricula to become more meaningful for students since the 1980s. In particular context-based education seems the most useful to support conceptual understanding of

abstract concepts.³⁸ Chemistry becomes meaningful and more relevant for students when they connect the abstract chemical concepts to real-world contexts.^{24,31,38} Teachers in context-based chemistry education focus on concepts and rarely on the daily life context, because they struggle with the context-based conceptualization.^{14,38,52}

A possible solution to making chemistry meaningful for students might be to use immersive virtual reality (IVR) in chemistry classrooms. IVR is seen as a promising tool for supporting students' meaningful learning.^{44,50,55} IVR can be described as a computer-generated world where users can interactively immerse and be present, while wearing a head mounted display (HMD). This gives the user a real feeling of being part of the scene and allows the user to practice new skills.^{16,51}

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IVR lessons implementing the characteristics of MCE identified in the mentioned projects to reform the chemistry curricula at secondary school level have not been detected to date.⁸ IVR content for chemistry learning with a daily life context is limited.¹³ The aim of this study was to identify IVR features that can support MCE.

THEORETICAL BACKGROUND

Meaningful Chemistry Education

Characteristics identified from the projects involved in redesigning chemistry curriculum materials to improve students' interest in learning chemistry (e.g., Salters) are (1) using a context that connects with students' daily lives; (2) the need-to-know principle; and (3) attention to students' input.^{30,60} Westbrook called these the "characteristics of MCE".⁶⁰ A fourth characteristic is the handling of chemical language: (4) the macro–micro connection.⁵⁶ These four characteristics of curriculum materials were used as a theoretical frame for this study and called the four "characteristics of MCE".

Characteristic (1), a context for learning to support MCE is defined as 'chemical concept learning within a daily life situation'. The context should fulfill the criteria that it connects with students' daily life; is relevant to chemical concept learning; supports chemical concept learning; and connects with students' prior knowledge. In this study, we describe a context from an activity approach (ref 57, p 481):

Context, then, is essentially conceived in terms of a sociocultural setting, calling for tool-mediated actions, operations, and goals that are to be valued in the framework of that activity.

A context that meets the four criteria of characteristic (1) is said to make meaning to students' chemistry learning and to their experiences of chemistry education as relevant to daily life.²⁴ These criteria should reduce the learning of isolated facts connecting context and prior knowledge and should support relevance and knowledge transfer in chemistry learning.²⁴

Characteristic (2)—the need-to-know principle—is described as a learning situation in which students recognize the problem; want to solve the problem; learn how to solve the problem; extend their knowledge; and are conscious of this extension. Students become intrinsically motivated based on these phases.⁴² This characteristic builds on students' existing knowledge and supports involvement of students in the learning process. Students can see the usefulness of what they learn, and as a result, students' involvement in the learning process is enhanced.⁶⁰ The need-to-know principle together with appropriate contexts has the intention to raise questions, which gives students a motive to extend their (prior) knowledge.¹¹ Students feel the need to learn the concepts to help them understand the daily life context.³⁸

Characteristic (3)—students' input for learning—is seen as a learning situation where students have some individual autonomy when learning and where they feel that their input matters. Students' input is closely related to the need-to-know principle. The problem-solving phases of the need-to-know principle are considered from the perspective of the students. The input of students is inevitable when students are expected to experience all phases. Students feel that their contributions matter when they have a certain autonomy of choice in the curriculum materials, where the teacher collects their input, summarizes, and categorizes it with attention to students'

input.⁶¹ In such an approach, students are more actively involved and more interested in the learning activities provided.^{5,10,60}

Characteristic (4)—the macro–micro connection—is a visualized connection between daily life phenomena (macro) and the micro-level of the particles, including models, processes, and molecules. Learning chemistry is difficult for students due to the complexity of the chemical language. Handling this chemical language mostly relates to models to explain chemical phenomena.⁵⁶ Three aspects of chemical language are involved, also called the chemistry triangle: (1) the macro-level, which encompasses the direct acting phenomena; (2) the micro-level, which is the level of the particles, including molecules, atoms, ions, bonding, etc.; and (3) the symbolic-level, which involves structure–property relations on the macro- and micro-levels.¹⁹ Teachers are known to switch easily between these levels, but for students as novices to chemistry, this is difficult, making it an obstacle to learn chemistry.⁵⁶ Teachers are expected to help students relate the macro- to the micro-level, so students are able to understand the chemical meanings behind the problems, avoiding fragmented chemistry knowledge and many misconceptions.^{47,64}

IVR to Support Education

Virtual reality (VR) is generally divided in two categories: nonimmersive VR and immersive VR (IVR). Immersion describes the user's experience of being within the virtual world. Presence is related to the user's experience of being able to react in a similar way as they would in a real-world environment.²⁸ In nonimmersive VR, or desktop VR, interaction with the virtual environment occurs between the user and a computer screen. The virtual environment can be influenced by a keyboard, mouse, or/and controllers.²⁸ In IVR, a computer simulation provides a multisensory, interactive simulated virtual environment while the user wears an HMD and can experience immersion and presence. The user feels a real part of the scene, similar to a real-life situation.²⁵ The immersive virtual environment experienced with an HMD secludes the user from the real world and allows the user interaction with the virtual environment. Multisensory interaction is achieved with the assistance of trackers and controllers. The trackers trace the users' position in the virtual environment and the controllers give the user the possibility to perform tasks.

IVR is said to be a promising tool to support meaningful learning.⁴⁴ IVR environments allow for more natural learning by doing and experiencing consequences of the own actions than learning by listening to lectures or studying books.^{26,66} The immersion and feeling of being present in an IVR environment involve multisensory learning, which is said to enhance user interest and facilitate student learning.^{21,55,65} In an IVR environment, all actions can be repeated, even in situations that are too dangerous or not accessible in classrooms or daily life.²⁸

IVR technology has been rarely implemented in education in the past mostly due to the high cost of the required equipment.^{7,35} Today, powerful smartphones are accessible to students and low cost (cardboard) HMDs are available.^{15,23} IVR technology has rarely been applied to authentic contexts for educational purposes or to support school curricula,^{29,45} and IVR applications for chemistry education are scarce.^{20,22}

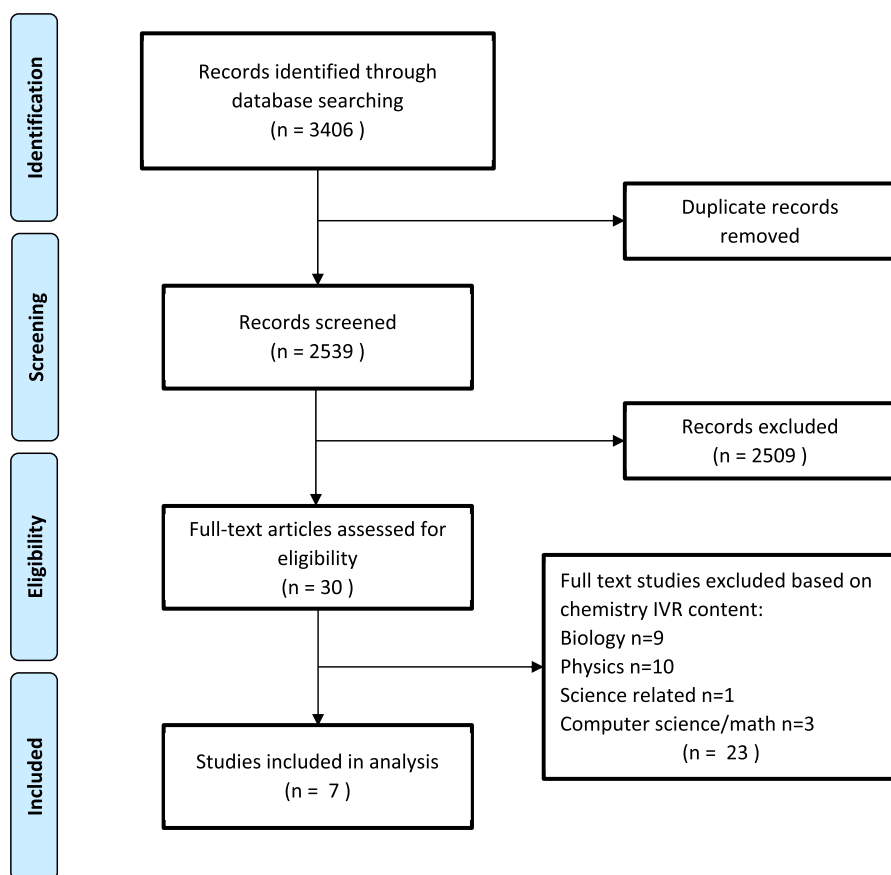


Figure 1. Flowchart of the literature search.

Two fundamental barriers to use IVR in the classroom are a lack of content and the hardware.²⁸ Animation-IVR based content provided by professional producers are mostly stand-alone experiences and not designed for different pedagogical approaches nor to be used at different educational levels. To introduce IVR in the school curriculum, teachers should have the opportunity to produce and edit their own IVR content. Affordable hardware (HMDs) is available⁷ but not designed for classroom use.²⁸ HMDs require technical support like software updates and user profiles. Streaming issues or preloading materials issues make it hard to handle a classroom full of HMDs simultaneously. HMDs are quickly outdated while the costs for multiple HMDs are high. A cardboard HMD together with powerful IVR-ready smartphones, which are readily accessible to students, could be a good alternative.²⁸

An animation-IVR is a computer generated interactive multisensory simulated environment, which can be experienced with a HMD.³ The user is perceptually surrounded and can interact with objects in this immersive virtual environment, using controllers. Realistic animation-IVR learning environments provide users to immerse and experience a realistic sense of presence and interactivity.⁴¹ To achieve this, high-cost HMDs and equipment like heavy duty computers are needed. Due to the complex technical design process, an ICT specialist is required to design an animation IVR. Classroom use with multiple users is difficult to achieve because of the space that is needed for the setup and the high costs of the equipment.⁴⁹

Teachers must have the ability to produce and edit their own IVR applications, in order to use it at different educational levels and with different pedagogical approaches.²⁸ 360°-IVR

based content is more opportune for teachers to produce and edit their own IVR content.²⁸ 360°-IVR can be based on a 360°-image or 360°-video. The user wears a (cardboard) HMD. A 360°-image is an image with the ratio 2:1, which can be taken with an omnidirectional camera or designed in a photo editing program. In 3D, the image is round folded like a ball. The user's view of the real world is blocked, and the user is positioned in the middle of this ball, the center of the scene, from where the user can look around.^{4,58} A 360°-video is a panoramic video, recorded using an omnidirectional camera. The user's view is blocked from the real world, and the user is positioned in a circle and has a continuous vision of the scenes.⁴

In 360°-IVR, users can change their field of view by physical moving the HMD or with the point-and-click technique. They can look around but cannot move or teleport to another location in the scene nor interact with objects. Only simple triggers, like opening tags with information or opening new scenes, are possible.^{50,59} 360°-IVR can be designed with relatively low costs. 360°-IVR can be viewed on many common devices like smartphones and (cardboard) HMDs. Omnidirectional cameras, HMDs, smartphones, and technology to create 360°-IVR are affordable and accessible to the public.^{29,66} It is possible to use cheap cardboard HMDs or to use stand-alone HMDs. Stand-alone HMDs are not wired and do not need a heavy-duty computer.²

RESEARCH QUESTION

The characteristics of IVR outlined above suggest IVR to be a promising tool to support MCE. The aim of this study was to

Table 1. IVR Requirements to Support MCE

	IVR requirements
Context: Connects with students' daily life; Relevant to chemical concept learning; Supports chemical concept learning; Connects with students' prior knowledge	Connect a daily life situation to a chemical concept to be learned. Context and concept are relevant to each other and connect with students' prior knowledge
Need-to-know: Students recognize the problem; Students want to solve the problem; Students learn how to solve the problem; Students extend their knowledge; Students are conscious of extending their knowledge	Visualize a daily life problem that appeals to the students and guide students to learn the chemical concepts to solve the problem. Feedback is given to proper analysis of the problem and a solution to the problem is offered
Students' input: Individual autonomy of learning; Students feel that their input matters	Students explore autonomously. A consequent solution to the problem is offered after a proper analysis
Macro–micro connection	A situation at the acting (macro-)level is directly connected with a visualized and explained model at the micro-level.

identify and investigate features of IVR in a secondary chemistry classroom to support MCE. The following research question was asked:

Which (design and implementation) IVR features can support MCE at secondary level?

METHOD

We used Educational Design Research (EDR) as a methodology for this study. EDR is said to develop research-based solutions to educational problems, using the design and development of interventions.⁴³ In this study, the first phase of EDR is presented: features of IVR were identified from the literature, experts' experiences were collected, and a first round of IVR lessons was developed and tested.

Literature Search

The literature search included peer-reviewed publications that are relevant to determine the value of IVR in secondary chemistry education, from 2010 to 2021. The focus of the search was IVR in secondary chemistry education.

Databases ERIC, Scopus, and Web of Science (WoS) were searched with keywords: ("Virtual Reality" OR VR) AND ("immersive" OR "HMD" OR "360") AND (education OR "chemistry education" OR "secondary education" OR "STEM education").

The search generated a total of 3406 publications. Duplicates ($n = 867$) were removed. Two thousand, five hundred and thirty-nine publications remained for primary screening, based on title and abstract. See Figure 1 for the flowchart used following the literature search.

After screening of the 2539 publications, 2509 publications were excluded. Publications were excluded based on the content containing nonrelevant techniques; on the content being outside educational settings, not science related, or not written in the English language; on the educational setting other than the natural sciences; on the purpose of the IVR (game-based, multiuser); and on there being no results of the described studies, review studies, and studies not in secondary education.

This screening resulted in 30 publications that claimed a setting with science education on secondary level and the use of IVR. These publications were systematically sorted on eligibility, namely, focused on chemistry education. Seven publications remained, containing content in the field of chemistry, which were analyzed on the quality of the studies and on students' experiences and learning with IVR (see the Results section).

Expert Feedback

IVR experts were consulted on necessary features of IVR in education, to explore their experiences. These experiences were used to underpin the design of IVR lessons and the literature.

Eleven IVR experts were interviewed. Two of them were IVR designers and IVR teacher trainers, one was a teacher and IVR teacher trainer, three were IVR designers, three were IVR designers and teachers, and two were teachers. Five of them had experiences with animation-IVR, three with 360°-IVR, and three with both. Semistructured interviews with the experts were conducted on didactic and technical features of animation-IVR and 360°-IVR in education, including IVR design, classroom use, and students' experiences.

IVR Lessons

The IVR lesson interventions involved three cases: two in animation-IVR and one in 360°-IVR. The content requirements to make IVR operational in classroom with implementation of the characteristics of MCE are depicted in Table 1.

The four characteristics of MCE were operationalized in the IVR lessons. The context was a daily life situation on environmental issues, which are part of the chemistry curriculum at secondary level, and that were recognizable for students. A chemical concept was integrated including the macro–micro connection wherein students could see daily life from a chemical view. The need-to-know principle was operationalized in that students knew why they had to learn the chemical concepts. Students could make choices that had an effect on the IVR environment, which allowed for students' input.

Additional requirements were established:

- Target group: 3th class HAVO/VWO (10th grade)
- Intuitive: every student should be able to use the IVR application
- Programmed instruction: information provided when necessary and easy to find
- Interactive: students are immersed in the environment and can influence the environment within the possibilities of the equipment
- Classroom use: achievable in the classroom

Both animation-IVR lessons were designed in Unity and carried out/accomplished with a desktop computer connected to an Acer AH101 HMD. For the 360°-IVR lesson, 360°-images were made with a RICOH THETA SC. The IVR tour was created on the platform Thinglink, and the IVR lesson was accomplished with students' smartphones and cardboard HMDs. A storyboard was designed to outline the IVR content.

Two animation-IVR lessons were designed by professional designers guided by the first author and tested. The first animation-IVR lesson was designed with the goal to encounter the challenges designers have to face with, regarding the content when the characteristics of MCE were applied in an animation-IVR lesson. Eleven students tested the designed animation-IVR: five female and six male aged between 14 and

16. No audio was used in favor of content information and instruction in pop-up screens, instruction papers, and papers with theory.

The context connected with chemical concepts learning presented the lesson goal: learn the chemical concept acid–base, applied in a daily life situation of acid pollution in the soil, caused by drug dump. Students had to determine the pH and how much chalk was needed to neutralize the soil. This environmental pollution connected with students' daily life and concept learning was interactive visualized based on students' knowledge about acids and bases. Because of the visualization of the situation, it was supposed that students wanted to neutralize the soil to prevent damage of the environment. Students could learn chemical concepts and could find out which actions they could take to solve the pollution. Students could explore the IVR lesson like they preferred and used information in their own way, by walking around and manipulate objects with controllers. Students' lab work helped in solving the pollution. When students did the separation method (filtration), a model on the micro-level popped-up to show what happens on the micro-level when they did the filtration on the macro-level.

The first author took notes during meetings with designers to capture design features. The test with students was observed by the first author. The designers conducted a questionnaire on students' experiences after the test: what they were doing and thinking during and after testing.

The second animation-IVR (see Figure 2) was designed with the intention to focus on inserting a more interactive micro-

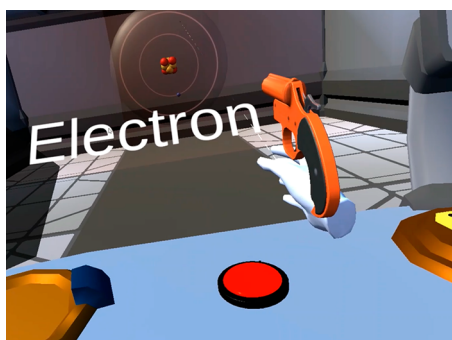


Figure 2. Animation IVR.

level. An interactive micro-level situation to build atoms was designed and connected to the macro-level, to identify the challenges designers had to encounter with the representation of an interactive micro-level. Seven undergraduate students (aged 18–22) tested different interactions of the micro-level during the design. This age group was chosen because they were better able to provide content feedback than the younger students the early version was tested with. The lesson goal was to learn the chemical concept acid–base and the composition of atoms, applied in a daily life situation of acid pollution in a lake caused by barrels filled with waste acid. Students had to build atoms by shooting the right amount of protons, neutrons, and electrons in position and convert these to complex ions, to neutralize the lake. The environment was designed, based on students' daily life and students' prior knowledge about the concepts, relevant to their chemical concept learning and with the prospective that students could learn how to solve the problem, wanted to solve the problem, and could extend their knowledge. Students could explore the actions to be taken in

their own way, guided by a talking lab assistant. After neutralization, the lake and environment turned healthy and green. During design, the first author made notes during the meetings with designers to capture the design features. The designers conducted a questionnaire with the students on the different interactions.

The third IVR lesson was with 360° (see Figure 3). Considering the benefits of 360°-IVR (see 2.5) compared to

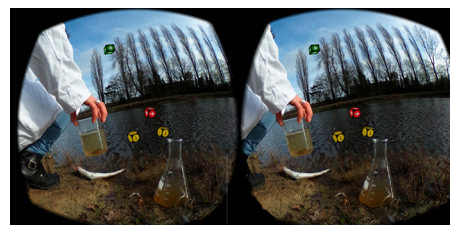


Figure 3. 360°-IVR.

animation-IVR, 360°-IVR to support MCE was designed by a teacher and the first author and tested in the classroom. Six students (aged 14–16) participated in the test. The lesson goal was to learn the chemical concept salts and applied to a situation of dead fish in a pond due to high concentration of salt caused by dumping slurry. Students had to determine the concentration of different salts and, if necessary, solve the high concentration problem. The 360°-IVR was designed with implementation of the characteristics of MCE, like the animation-IVR lessons. Thus, chemical concept learning in a daily life context with students' input and wherein students could see the usefulness of what they learn (prevent fish from dying). The micro-level was a model of the structures of the involved salt ions. No audio was inserted, and extra information and instruction was provided by tags. Design features were captured. The first author observed the students, asked them to fill out a questionnaire, and conducted a semistructured interview with them on their IVR experiences.

RESULTS

The design features that are most likely to support the best practices of MCE IVR use in classroom were identified from a review of the literature found, the interviews with the IVR experts, and the trial-runs with IVR lessons.

Literature Search

The seven identified papers (Table 2) are studies in which chemistry content was conveyed to secondary school aged participants using an IVR environment with an HMD. All papers used animation-IVR experimental designs.

The goals of the first three papers and the last one can be categorized as using IVR to visualize invisible chemistry for different reasons: adding to lectures,⁶ vital chemical knowledge on bonding,²⁰ and replacing and enhancing learning from chemical laboratory work.^{27,54} The goals of the other three papers can be categorized as using IVR in chemistry for more societal issues: gaining STEM interest,³² gender differentiated learning,³³ and understanding of a local environment issue.⁴⁶

In five of the seven papers, the IVR application was used to take the participants into the context of the micro-level of atoms and molecules. Two of the seven papers were set in a daily life context in connection with the micro-level, two in a laboratory setting, and two were connected to a chemistry curriculum concept. In one paper, the content is not discussed,

Table 2. Overview Identified Publications

reference	IVR content	age participants (years)	number of participants (male/female)	type HMD	publication type
6	atomic structures; Rutherford's gold foil experiment; Bohr's orbital model	14–16	10 (5M/5F)	Oculus Rift	poster
20	hydrocarbon bonding and molecular structures in organic chemistry	12–36	13 (6M/7F)	VR gear with phone	article
27	experimental chemistry learning in a context of a forest campsite	14–16	unknown	unknown type	article
32	Study 1: laboratory safety	Study 1: 13–16	Study 1:99 (52M/47F)	Samsung Gear with phone	article
33	Study 2: DNA analysis laboratory safety with avatar "Marie" or "drone" preference male/female	Study 2: 17–20 13–16	Study 2:131 (47M/84F) 66 (33M/33F)	Samsung Gear with phone	article
46	erosion study: view water molecules dislodging plant roots renewable resources study: adjust water salinity by opening/closing the freshwater inlet.	Erosion: 12–13 Resources: 12–13	Erosion: 30 (14M/16F) Resources: 100 (58M/42F)	Oculus Rift CV1	article
54	reaction rate	unknown, high school students	23 F (unknown)	Android based; shutter glasses	conference series

only that it is material on reaction rate. In all papers, the use and the effect of IVR for their particular goals were studied, none of which were used to assess student performance (i.e., grading).

Animation-IVR in a multisensory environment was included in all papers to interact with the content/manipulate the environment. Some IVR applications included hand-held controllers; some used other means of interaction such as a touchpad. All IVR applications included multisensory instruction and information in the shape of an avatar (audio) and/or texts, which students could use when they needed it. Affordable IVR equipment readily available at the time of study was used in each paper. One paper did not mention the IVR equipment used. In five papers, the use of the application was evaluated. In four papers, there was no clarity whether the IVR application was tested in a classroom setting. In the other three papers, the testing was not done in a classroom setting, two of which were tested during a science camp.

Most papers report that students experienced IVR engagement and more interest in the topic in such an environment. Students described an increase in science aspirations, motivation, the feeling of social presence, self-efficacy, and outcome expectations. Students experienced IVR as helpful in focusing attention. Most papers studied students' learning that was reported to have improved: a better understanding of the topic was found. Learning through IVR as a multisensory system indicated positive multisensory learning. Also, improved problem-solving performance and applying information to new situations were mentioned. Students were more inclined to talk about what they learned, which reinforced classroom learning.

Expert Feedback

Regarding IVR design: experts indicated that for animation-IVR a professional designer was needed, whereas 360°-IVR could be designed by teachers and students. Their opinion was that hiring a professional designer leads to high costs and will then probably be too expensive for individual productions in school. Editing a lesson designed by a professional designer induces more costs and inconvenience.

A well-defined storyboard was seen to be important for both animation-IVR and 360°-IVR because it could affect students' experience, albeit difficult to realize. Therefore, the experts emphasized that the learning goal needed to be well thought through and visualized properly. For animation-IVR, scientific

models were found to be difficult to visualize, especially on micro-level.

In terms of classroom use of IVR: the experts mentioned that IVR in general caused generative processing, took away misconceptions, and supported concept learning in students. Generative processing implies that students are more stimulated and motivated to understand the learning goal because of the high level of realism. Students were seen to be enthusiastic, more involved in IVR lessons, had more fun, and had a positive experience. Daily life and the micro-level were seen to be visualized interactively and connected. It was noticed that students had ownership of the learning route to make their own choices (need-to-know and students' input), and IVR could support learning goals in a safe interactive multimedia environment, wherein students could immerse and be present and repeat as often as necessary in situations that could not be done in the real world. According to experts, at the moment, no appropriate content was available (also not in coherence with lessons/curriculum).

Experts said that animation-IVR was difficult to do in classroom settings when every student needed a wired HMD with a powerful computer, but a wired HMD does give more interactivity. With a wireless HMD, more students could interact at the same time, but it was less interactive than with wired HMD. Experts indicated that HMDs had technical restrictions and animation-IVR needed service and updates. Controllers could not be used with students' smartphones for 360°-IVR because of the limited software and GPS function on the phone. Only pointing was seen to be possible but less interactive and less realistic, and moving around was limited.

Animation-IVR

Two animations were tested. This section is divided into two parts: the first showed the results of both animations in terms of features during animation-IVR design and the second is in terms of observations and a questionnaire of animation-IVR use in classroom.

During the design of animation one, the storyboard was fine-tuned and included the selected requirements and the lesson goal to (not chemistry educated) professional designers to make the application intuitive. This kind of IVR had to be designed by designers. The usefulness of the interaction was not at the expense of the chemical content. No chemical misconceptions were identified. Fluid was difficult to depict in

IVR. The micro-level was not interactive and only connected with the macro-level.

During the design of animation two, the focus was on the micro-level, building atoms to solve the pollution problem. A well-defined storyboard, with the design criteria, was used. To build an atom, several problems were faced to make it chemically correct: only simple atoms could be made (because of the visibility and complexity); the amount of neutrons in the nucleus depends on the isotope to build and the most relevant isotope was used; in order to pick up the build atoms, these had to be stored in a transparent box; the necessary complex ions were composed in a machine and came out in different bottles because it was not possible to visualize (throw in H-atoms and O-atoms and a bottle such as OH^- came out the machine). The professional designers struggled with the micro-level models to be chemically corrected (with gaming they could use their imagination).

The use of animation one was observed. Students familiarized themselves with the controllers quickly. Some said it was a weird experience to be in a virtual world and to teleport instead of walking. Three of the 11 students were gamers, and they performed very easily and were controlled from the beginning. Some students needed extra instructions during the actions. Two female students mentioned nausea. Students were enthusiastic about the IVR experience. The approximately 10 minute test took place in a separate room because of the equipment. In the questionnaire of animation, one student indicated that they experienced the instruction as clear, the IVR lesson as intuitive and not difficult to use, and they liked the lay-out. Students liked the IVR lesson because it was informative in an exciting way and different from normal lessons. They liked being interactive the most, picking up things and walking around/teleporting. Getting skilful, they liked the least. Most students wanted to use IVR more in chemistry, because it was “nice” and “informative” and “you learn more if it is nice and more modern”. Most students thought that they understood chemistry better with IVR because an experiment always helps to understand and this was easier to do than in real life.

Different interactions/settings of atom building were tested in animation two. Students who tested the five settings indicated that it felt natural and that they enjoyed it. The most natural feeling was the most enjoyed, but this was the most distracting from the actual atom building process. The early version was tested, and students said that the instruction of the IVR lesson and use of the equipment was intuitive but that a reset button was missing. The environment was not intuitive to navigate, and more information to perform was needed.

360°-IVR Design and Use in Classroom

The design of the 360°-IVR lesson was laid out on a storyboard and included the selected requirements and the lesson goal. A readily available software program (Thinglink) was sourced and explored to design the 360°-IVR lesson in. The micro-level and macro–micro connections were included by inserted pictures behind buttons. No chemical misconceptions were identified. Objects in the 360° environment cannot be manipulated.

The use in classroom was observed. Some students had start-up/technical problems with their smartphones. Students were interested and enthusiastic, and some students were observed exchanging information. Interaction in the lesson was limited to the point and click method. All students could do

the IVR lesson at the same time. Results from the questionnaire supplemented with the in-depth interview answers showed that instruction and navigation was intuitive. Students liked that they could intuitively foresee what would happen in the situation and they experienced real involvement. Students indicated that chemistry learning could be improved in this way and that chemistry learning was more enjoyable. Five-sixths of the students preferred learning in a daily life situation. They indicated that they could understand the chemical content better with IVR. Only half of the students wanted the environmental issue to be solved; the issue did not appeal to all students. Two-third of the students liked to make their own choices in the route (e.g., the use of buttons), although a minority of the students preferred clear instructions without choice. Students thought that understanding would improve if you could go back during the IVR tour. The macro–micro connection was not clear for three-fourth of the students, because they did not understand the difference between the macro- and micro-level (yet).

DISCUSSION OF RESULTS AND CONCLUSIONS

In this section, the established design and implementation features of animation- and 360°-IVR are discussed in relation to the four characteristics of MCE. In addition, the application of IVR to support meaningful chemistry learning in future studies is outlined.

The four identified characteristics of MCE include chemical concept learning integrated in a daily life situation (context connected with daily life), in a way that students need to know why they have to learn the chemical concept (the need-to-know principle), with a certain autonomy of choice (students' input), and the connection between the visible and reacting particle level (the macro–micro connection).^{56,60} These characteristics were identified in the IVR literature search on secondary chemistry education, even though not specifically named and spread across the papers. Daily life situations were connected to the micro-level,^{27,46} and students could use information when needed and could interact with the environment.^{6,20,27,32,33,46,54} Experts identified the MCE characteristics in IVR lessons. This supports our claim that the four characteristics can be applied in IVR lessons. The combination of the IVR requirements and the characteristics of MCE together can be powerful features to support MCE in future IVR designs.

The powerful design features identified in this study to support MCE in IVR designs could be applied to both animation- and 360°-IVR lessons. Animation-IVR is more interactive than 360°-IVR. A professional ICT designer is needed in animation-IVR, while in 360°-IVR, teachers can be the designers. Classroom use with all students at the same time is limited with animation-IVR because of the expensive equipment and the area needed. The necessity of a storyboard to design and the difficulties in realizing interactive visualization are similar between the two forms of IVR.

In terms of the implementation of the identified features, the classroom test of the animation-IVR and 360°-IVR revealed positive outcomes regarding students' experience and learning. In general, the students perceived the added value of the characteristics of MCE, to improve chemistry learning. Students enjoyed the IVR lessons; it was motivating and they thought they could better understand chemistry, which was also found in the papers of the literature search, and expert feedback. Literature reviews of IVR in education, albeit none of

them specific to chemistry education and describe positive experiences of students with IVR (e.g., increased engagement). The reviews also showed positive results on students' learning with IVR (e.g., increased understanding of the topic).^{12,16,18,25,28,40,53,63} It is argued that both animation- and 360°-IVR foster high motivation, and learning outcomes are similar and higher than with nonimmersive desktop VR.^{1,4,39,49} In addition, 360°-video is the least interactive IVR,⁴ and the level of presence in 360°-IVR can be supported by both affective content and immersion.⁴⁹

As positive learning outcomes were not found to be connected with specific design features,³⁴ different IVR lessons are possible. To design and apply IVR lessons, first, the preconditions have to be considered, including the available money and lesson goal. For example, if one wants to apply IVR lessons with low cost, with all the students at the same time and designed by oneself, 360°-IVR is probably preferred. But, if one can cover the financial expense and only highly interactive IVR lesson is desired, or for individual students only, one might consider animation-IVR. When the kind of IVR (animation or 360°) and the equipment is decided on, the content needs to be created carefully in a storyboard. The four characteristics of MCE have to be included in the lesson, and the interactive visualization of the IVR lesson needs to be scientifically correct and clear to students. When the IVR lesson is designed satisfactorily, it can be used in classroom and if necessary redesigned.

The results suggest that IVR can be a beneficial resource for making student learning of chemistry (at secondary level) meaningful and for increasing their interest. When chemistry learning improves by making it meaningful, student interest and motivation for chemistry are likely to increase.⁵² The reform of the chemistry curriculum (in The Netherlands 2013) supports meaningful learning, but teachers have struggled with this. In this study it is claimed that the use of IVR in particular areas of chemistry education might help to support meaningful chemistry learning. To confirm these results for chemistry education in other contexts, future research needs to be done. More IVR-lessons can be designed based on the features found in this study, in particular, the characteristics of MCE, and tested with more participants to study whether this indeed is beneficial for all students. As chemistry education is crucial for an understanding of the natural world, this study is important to establish and apply IVR in future chemistry education to motivate students' chemistry learning in a meaningful way.

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Notes

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