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The Perceived Complexity of Learning Tasks Influences Students' Collaborative Interactions in Immersive Virtual Reality

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Abstract

This study investigated how different learning tasks influence students' collaborative interactions in immersive Virtual Reality (iVR). A set of chemistry learning activities was designed with iVR, and 35 pairs of undergraduate students went through the activities. Videos of students' interactions were analysed to identify patterns in students' physical, conceptual, and social interactions. When students were manipulating conceptually familiar virtual objects (several water molecules), they perceived the tasks as a simple extension of prior knowledge and did not attempt to explore the 3D visualisation much. They did not move around to take different perspectives, and conceptual discussions were brief. Their prior power relations (leader–follower) carried over in iVR environments. In contrast, when conceptually unfamiliar chemical structures (protein enzyme) were displayed, students perceived the tasks as complex, demanding a new mode of learning. They spontaneously moved around to explore and appreciate the 3D visualisation of iVR. Walking to different positions to observe the virtual objects from multiple angles, students engaged in more collaborative, exploratory conceptual discussions. As the perceived complexity of learning tasks or virtual objects triggers different collaborative interactions amongst students, careful considerations need to be placed on the design of iVR tasks to encourage productive collaborative learning.

Keywords Immersive virtual reality · Human–computer interaction · Collaborative learning · Chemistry education

Immersive Virtual Reality (iVR) technology for educational purposes has gained widespread popularity in recent years (Radianti et al., 2020). Using head-mount displays, iVR engrosses students in realistic-looking 3D computer-generated environments where they can interact intuitively. This enhances their feelings of "being there" in the virtual environment and actions having real consequences (Slater & Sanchez-Vives, 2016). The unique 3D visualisation and motion-tracking features of iVR present opportunities to address key educational challenges (Slater & Sanchez-Vives, 2016). Consequently, science educators have started exploring the educational possibilities of iVR to support students' visualisation of abstract concepts, enhance learners' engagement, or train practical skills (Matovu et al., 2023a).

Of the different science learning areas, chemistry could significantly benefit from iVR. For instance, iVR can simulate 3D molecular structures, such as protein structures, which cannot be visualised or explored easily through other means (e.g., Qin et al., 2021). By transforming abstract chemistry concepts (e.g., molecules and their interactions) into tangible forms, iVR could support students' construction of useful mental models of the concepts (Mikropoulos & Natsis, 2011). Students can examine spatial relations (e.g., depth and angles) in 3D molecular structures from different viewpoints (Dede, 2009). Students can also manipulate the molecular structures in an embodied way to actively construct knowledge (Chen, 2010).

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However, science education researchers have mainly provided one-time learning opportunities with iVR, without exploring how different learning tasks would influence students' experiences and learning (Matovu et al., 2023a). The few researchers who provided multiple iVR opportunities to students (e.g., Huang et al., 2021; Pande et al., 2021) relied on pre-/post-knowledge tests without documenting how students' interactions in iVR evolved over the learning sessions. In addition, iVR-based learning activities have been designed and tested mostly for single users, without utilizing collaborative knowledge construction processes (Matovu et al., 2023a, Won et al., 2023). Few researchers have explored students' collaboration to complete interactive science learning tasks in a shared iVR space (e.g., Won et al., 2019; Southgate et al., 2019). These studies relied on evaluations based on observations (Southgate et al., 2019) and interviews (Won et al., 2019), rather than comprehensively documenting students' interactions in iVR.

To gain a more balanced perspective of the educational potential of iVR, researchers need to explore how students' interactions change across different iVR-based learning contexts. By documenting changes in students' interactions with the nature of the learning tasks or virtual objects, educators can identify and design iVR-based learning tasks that can optimise students' collaborative interactions. In the present research, we designed a set of iVR-based learning tasks to help undergraduate students collaboratively learn chemistry topics on molecular interactions and evaluated the changes in students' collaborative interactions.

The present study was designed to support students' 3D visualisation of chemical structures and interactions. The skill to visualise these concepts is fundamental to the learning of chemistry yet challenging for many students (Wu & Shah, 2004). This study employed iVR to effectively represent molecular structures in tangible forms, enabling students to interact with these representations intuitively and support their understanding of intermolecular interactions. The research study was also theoretically informed by the social constructivist theory of learning (Vygotsky, 1978), which emphasises social interactions as a driver of learning. Within iVR contexts, students were paired and encouraged to engage in coordinated efforts to create joint meanings and complete chemistry learning tasks. Such collaborative interactions involve a dynamic engagement with different ideas through verbal interactions, actions with artefacts, and non-verbal interactions, such as gestures and facial expressions (Hakkarainen et al., 2013; Roschelle & Teasley, 1995). Collaborating on learning tasks provides students with an opportunity to generate varied perspectives for consideration, engage in self-reflection, and organise and revise their understandings through reciprocal explanations (Webb, 2009, 2013).

Collaborative Interactions in Digital Learning Environments

Various forms of digital technologies offer opportunities for collaborative learning interactions in unique ways. Video conferencing platforms (e.g., *Zoom, or Skype*) allow students to communicate verbally and non-verbally in real time, but students are in different physical spaces and cannot manipulate shared objects. Multi-user virtual worlds on 2D screens (e.g., *Second Life, or River City*) provide a common ground for spatially distributed students to meet and work collaboratively on learning tasks (Dalgarno & Lee, 2010). However, in these environments, students are represented by avatars, communication is often through text, and students manipulate objects using a keyboard and mouse. In contrast, collaborative iVR platforms (e.g., *AltSpaceVR*, or *Engage VR*) allow students to physically walk into a shared virtual space to interact with peers in a first-person perspective, making them feel physically co-located with their peers (Šašinka et al., 2019). Students can communicate verbally with peers, use gestures for non-verbal communication, and use their "hands" to manipulate shared virtual objects and co-construct understanding (Won et al., 2019; Maloney & Freeman, 2020). Students' movements in the virtual space match their movements in the real world (Barreda-Ángeles et al., 2023). As a result, collaborative interactions in iVR feel more "real" compared to other digital technologies (Barreda-Ángeles et al., 2023; Oh et al., 2018).

Although iVR could mimic face-to-face collaborative interactions, the implementation of social interactions in iVR for learning has been slow (Won et al., 2023). Efforts to incorporate social interactions mainly employed iVR designs where learners interacted with pedagogical agents for step-by-step guidance, rather than supporting collaborative knowledge construction with peers (e.g., Makransky et al., 2019). Some researchers incorporated peer-to-peer interactions by having one student in iVR and the other observing the virtual environment on a 2D screen (e.g., Price et al., 2020; Uz-Bilgin et al., 2020; Webb et al., 2022). The student using a 2D screen missed out on the opportunity to experience virtual objects from a first-person perspective.

Some educators have used open-source collaborative iVR platforms (e.g., *AltSpaceVR* or *Engage VR*) to engage students in social interactions (e.g., Barreda-Ángeles et al., 2023; Han et al., 2023; Ripka et al., 2020). However, these researchers used iVR as a place for distributed students to meet and brainstorm ideas, rather than as an environment to interact with virtual objects. Consequently, these studies have not explored how students utilise the unique iVR features (e.g., 3D visualisation and embodied movements) to collaboratively learn abstract science concepts.

Studies on technology-mediated collaborative learning also showed that assigning group tasks does not guarantee effective collaboration (Kreijns et al., 2003). For example, students who lack communication skills may struggle to negotiate ideas with others, leading to conflicts and unproductive conversations (e.g., Barron, 2003). In addition, some students may be less motivated to participate in collaborative activities, relying on the more active learners (Zhang et al., 2019). This can result in frustration for the active learners, who may also become less engaged (e.g., Lipponen et al., 2003).

Researchers note the importance of pedagogical considerations (e.g., task design) and social factors (e.g., group composition) in producing collaborative interactions when designing digital learning environments (Kirschner et al., 2008). For example, students' perceptions of task complexity influence how much effort they invest to complete the task. Tasks that are too easy, leave no room for student initiatives, or too closed offer little room for discussion and tend to limit collaboration (Kirschner et al., 2008). Too complex a task would also lead students to withdraw from tackling (Malmberg et al., 2022), but when the task requires students to draw from each member's perspectives, it tends to promote collaborative engagement (Care et al., 2015). A sense of cohesion amongst group members and relational history also contribute to collaborative interactions (Graesser et al., 2018; Kreijns et al., 2022). Yet, existing studies have not explored how the nature of learning tasks influenced collaborative interactions in iVR. More studies are needed to explore how such task-related factors influence students' collaborative interactions in iVR.

The present study explores how student pairs collaborate to complete chemistry tasks with different kinds of virtual objects in three iVR-based learning contexts. To illustrate the differences in students' interactions, this research focused on two of these iVR contexts, one with conceptually familiar virtual objects and one with conceptually unfamiliar virtual objects. The learning tasks in these iVR contexts targeted the topics of hydrogen bonds in water molecules and enzyme–substrate reactions, respectively. This research aimed to answer the following research questions:

- How do students collaborate to learn intermolecular interactions with water molecules in immersive Virtual Reality?
- How do students collaborate to learn the same concept with an enzyme and a substrate molecule in immersive Virtual Reality?

Methods

Participants and Data Collection Procedures

Seventy first- and second-year undergraduate chemistry students at a large public university in Australia volunteered to participate in this study. As part of their chemistry units for semester 1 (March–May 2021), the students in pairs completed three iVR sessions (snowflake iVR, taste receptor iVR, and protein iVR). Any two consecutive iVR sessions were spaced 2–3 weeks apart. Students selected convenient time slots outside their normal class schedules. Because of this flexibility, some students were paired with peers they had worked with prior (*friends*), while other pairs did not know each other (*strangers*). Participants worked with the same peers over the three iVR sessions.

Each iVR session involved a pre-interview (15–25 min), an iVR learning activity (25–50 min) and a post-interview (20–30 min). In pre-interviews, students (in pairs) were introduced to the target topics and their prior understanding was evaluated. In pre-interviews for the first iVR learning activity (snowflake iVR), students were asked to explain and illustrate how water molecules would interact in snowflakes. Similarly, before the last iVR learning activity (protein iVR), students were asked to describe and illustrate their understanding of enzyme–substrate reactions. After pre-interviews, participants were trained on using iVR controllers to manipulate virtual objects and were encouraged to discuss ideas with peers, move around the virtual space to explore objects from different perspectives, and immediately report any discomfort during iVR. Each student then donned an HTC VIVE Pro Eye headset with a wireless adaptor and two controllers for iVR-based learning. In iVR, students could walk around a 4m x 4m room to complete learning tasks. They could also see each other's avatars (floating headsets and hands) in a shared virtual space and communicate verbally. In post-interviews, students reflected on their learning experience and answered conceptual questions to evaluate their learning. All pre-/post-interviews and iVR activities were audio and video recorded to capture students' conversations, movements, and physical actions in the physical room. Videos of each student's view in iVR were also recorded using a screen-recording application.

The Collaborative iVR-Based Learning Tasks

The three collaborative iVR activities were developed by the research team. First, storyboards were developed highlighting the target learning objectives, tasks, and instructions to students. The iVR programs were then developed in Unity® and were run with STEAM VR as the supporting platform. In each iVR activity, student pairs completed multiple interactive tasks. In the first (snowflakes) iVR activity, students explored the nature of hydrogen bonds between water molecules in snowflakes. The tasks included forming and exploring the strength of a hydrogen bond between two molecules (e.g., Fig. 1a) and constructing a lattice structure of water molecules to explain the shape of snowflakes. In the second (taste receptor) iVR activity, students explored the concept of stereochemistry using the chemical phenylalanine. Learning tasks included constructing two enantiomeric forms of phenylalanine and fitting them in a model of a sweet taste receptor to identify the form that would activate the taste receptor. In the last (protein) iVR activity, students explored the reaction between an enzyme (acetylcholinesterase), and its substrate (acetylcholine) in relation to chemistry concepts. Learning tasks included exploring the structure and the best orientation of the substrate molecule to enter and react with the enzyme (e.g., Fig. 1b). In all iVR learning environments, the key conceptual ideas were (1) molecular shapes and orientations; and (2) attractions between electron-rich (red) and electron-poor (blue) areas. To complete the key learning tasks in each iVR environment, students needed to apply these conceptual ideas to position the 3D molecules in optimal orientations so that they would interact.

Data Analysis

For each student pair, we first synchronised the videos of students' interactions in the physical space, audio records, and their views of the virtual world during each iVR activity. Synchronising these records facilitated the tracking of students' interactions in both the virtual and physical spaces simultaneously. The synchronised videos were then used to create multimodal transcripts (Cowan, 2014; Walkington et al., 2023) encompassing multiple forms of data. The data included students' talk, positions, visual foci, physical movements, gestures, interactions with virtual objects, and screenshots. This approach was chosen because social interactions are inherently complex and involve multiple communication modes (Jewitt, 2013). Multimodal transcripts, thus, make contextual information and moment-by-moment developments in students' collaborative interactions visible to aid the analysis (Walkington et al., 2023). For example, examining students' relative positions in the virtual and physical spaces allowed us to analyse students' perspectives of and proximity to virtual objects and peers during collaborative iVR activities. Students' speech, gestures, and interactions with virtual objects provided insights into students' ways of reasoning with molecular structures and how they responded to or built off each other's reasoning.

The research team met to watch synchronised videos and identify some notable aspects in the interactions. We analysed the videos in terms of students' physical interactions (nature and sequence of movements, positions in iVR space, and actions with virtual objects), conceptual exploration (what chemistry concepts were discussed), and social dynamics (how peers generated, expressed, and elaborated ideas, negotiated control of virtual objects, and established consensus).

Based on the analyses of students' pre-interview diagrams and preliminary analyses of iVR session videos, we purposefully selected 10 out of the 35 student pairs for in-depth analysis. These pairs demonstrated a reasonable (but not comprehensive) understanding of the target topics in pre-interviews and engaged in deliberate conceptual explorations in iVR. The first author analysed interactions for all 10 pairs of students using a constant comparison method (Glaser, 1965) to identify any emerging patterns. Student-generated diagrams and responses during pre-/post- interviews were used to triangulate findings from the analysis of iVR session videos. Three researchers (HM, MW, and RBHA) watched selected segments of iVR session videos together and discussed the patterns in students' interactions. The process was repeated over several months until an agreement was reached.

Findings

Our analysis showed that the different iVR-based learning contexts prompted different physical, conceptual, and social interactions among the students. When dealing with conceptually familiar virtual objects (water molecules) in snowflakes iVR, students engaged in short conceptual and physical explorations. Among strangers, the peer perceived as more knowledgeable dominated the generation of ideas and/or manipulation of objects but this dominance did not occur among friends. In an environment with conceptually unfamiliar virtual objects (enzyme and substrate structures)

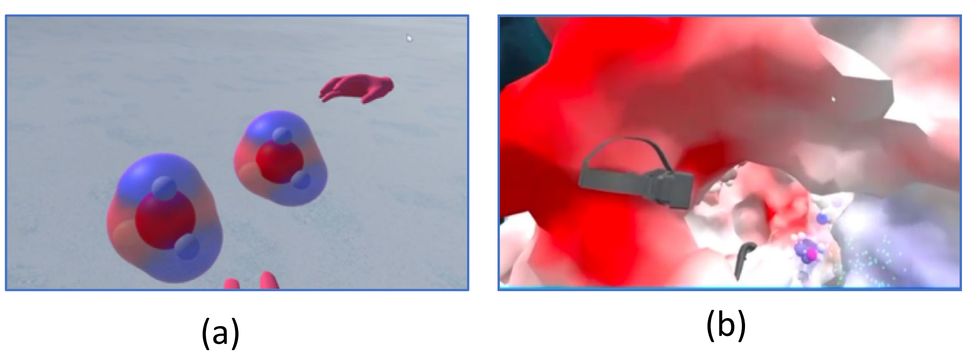


Fig. 1 **a** Two water molecules in snowflakes iVR. **b** Part of an enzyme passageway in protein iVR

in protein iVR, students exerted more effort to collaborate and learn. Students explored the protein iVR environment extensively and integrated multiple chemistry concepts to complete the tasks. The dominance of one peer over another among strangers also disappeared.

We have arranged the results sections in two parts. **Part 1** illustrates students' interactions and social dynamics when exploring water molecules (conceptually familiar objects) in snowflake iVR. **Part 2** illustrates students' interactions and social dynamics when exploring enzyme and substrate molecules (conceptually unfamiliar objects) in protein iVR. In each part, we first provide an overview of students' interactions while completing the focal tasks in each learning environment. The findings are then illustrated with a more detailed analysis of one pair of students (pseudonyms Noah and Jesse).

Part 1: Students' Interactions with Conceptually Familiar Virtual Objects

The focal task in the snowflakes iVR activity involved exploring the features of water molecules and the nature of hydrogen bonds between two water molecules. Although hydrogen bonds are a concept many students felt comfortable with, their diagrams and verbal explanations in the pre-interview showed varied levels of understanding. All ten pairs acknowledged that a hydrogen bond is an electrostatic intermolecular force, but many of them (seven pairs) were unsure of the role of lone pairs or the direction of a hydrogen bond. Only two pairs mentioned that hydrogen bonds would form because of molecular interactions in 3D space.

In iVR, students were amazed by the models of water molecules—the structure and electron density map were displayed in 3D. Students immediately grabbed one virtual water molecule each, rotating and pointing out the features (hydrogen atoms, oxygen atoms, lone pairs, red cloud for electron-rich, and blue cloud for electron-poor areas). When prompted to form a hydrogen bond, many students overlapped or stacked water molecules (e.g., Fig. 2a). Even though they had a rough idea of the role of oxygen's lone pairs, they struggled to use that knowledge to form a hydrogen bond between two water molecules in the 3D iVR environment (Fig. 2b). After several trial-and-error attempts, most students (8 pairs) managed to create a hydrogen bond by positioning water molecules at a reasonable distance and angle, but they did not change their perspectives to check the alignment of water molecules to take advantage of 3D visualisation. Since the water molecules looked simple and conceptually familiar, students felt that they had already explored the concepts through other media and that they could seamlessly apply their prior understanding to 3D objects. As such, in iVR, many tried to orient the molecules the same way they had represented them in their 2D diagrams, for example stacking molecules (Fig. 2a). Also, students did not feel compelled to walk around the virtual objects or explore different perspectives since they normally do not need to while drawing diagrams on paper or exploring the concepts on computer screens.

Students' social dynamics showed distinct variations between strangers and friends. Among strangers, students who used keywords such as "electrostatic interactions" and "electronegativity" in pre-interviews were perceived as more knowledgeable by their peers and often assumed dominant roles. These leader–follower relations extended into iVR. As students explored hydrogen bonds between molecules, the peer perceived as more knowledgeable typically assumed a dominant role in manipulating molecules and generating ideas, while the less knowledgeable peer kept their ideas to themselves. Students with higher perceived prior knowledge felt confident to apply their knowledge in iVR and persuade their peers, while those perceived as less knowledgeable felt that their peers possessed enough prior knowledge to complete the iVR tasks. In contrast, such unequal relations were not evident among friends. Friends freely shared their thoughts and contributed equally in iVR. Perhaps the pre-existing rapport among friends facilitated communication and enabled them to work together effectively. For instance, a friend would know how to elicit ideas without claiming authority and would easily be able to detect divergent opinions.

(a) Stacking molecules: Directly replicating 2D orientations in iVR

(b) Overlapping molecules: Difficulties applying prior knowledge in iVR

Fig. 2 Students' initial attempts at forming a hydrogen bond between water molecules

The Case of Noah and Jesse Interacting with Conceptually Familiar Virtual Objects

Noah and Jesse were first-year chemical engineering majors who had not worked together before the iVR activities. Both had no prior experience with iVR but regularly played computer games. Before iVR, both illustrated each water molecule forming four hydrogen bonds but did not mention the 3D nature of these interactions (Fig. 2b). Jesse was more confident articulating his ideas and used more scientific language with keywords, such as "polarity" and "electronegativity". Recognising Jesse's proficiency, Noah was more reserved and perceived Jesse as more knowledgeable.

Water molecules in iVR are represented as white and red spheres (hydrogen and oxygen atoms) surrounded by blue and red clouds (electron density map over hydrogen and oxygen atoms). Upon seeing the water molecules in iVR, both students engaged in generating ideas but did not negotiate much. Jesse focused on the electron density map (the cloud): *"It does not look like normal atoms but a cloud of possibilities"*. Noah remarked that he was not sure but identified the red sphere as the oxygen atom and the white spheres as the hydrogen atoms. Instead of acknowledging or building on Noah's idea, Jesse expanded his idea of the cloud: "*I think the cloud, the red [cloud] is oxygen, blue ones [clouds] are hydrogen, and the white ones (spheres) are bond sites.*" Without further discussion, Jesse then asked Noah to press the submit button and move to the next task. Jesse was confident that the concept was familiar—water molecules are only represented differently. Therefore, he did not feel compelled to explore the virtual objects or new ideas, which led him to miss out on the opportunity to recognise other concepts such as the lone pairs of electrons, or molecular geometry in the molecules. Moreover, the fact that Jesse focused on more advanced features (the cloud around the molecules) may have confirmed Noah's impression that Jesse understood the concepts better. Consequently, Noah did not negotiate much but simply followed the peer.

When prompted to form a hydrogen bond, the students took turns grabbing and orienting the two water molecules. Despite demonstrating a reasonable understanding of hydrogen bonds in their pre-interview diagrams, the students overlapped the molecules without aligning a hydrogen atom of one molecule with a lone pair of electrons on another molecule (Fig. 2b). They might have found it hard to apply their prior knowledge in the 3D iVR environment. Each student then experimented with their ideas without narrating their actions. They did not negotiate much and simply moved to the next step even though no bond had formed.

Jesse's dominance became more pronounced when the students were prompted to make the hydrogen bond stronger (Table 1). Jesse reflected on what they had achieved earlier and continued testing his ideas before the hydrogen bond (a green stick between molecules) suddenly formed (Turns 1–3). He then continued with the role of the "leader", dominating the discussion about the features of the bond and prescribing further actions (Turns 4–9). Even after inviting the peer's participation, Jesse kept manipulating virtual molecules (e.g., Turns 4–6). Conceptual discussion relied heavily on Jesse who introduced concepts, such as the formation of a hydrogen bond (Turn 6) or the effect of the angle between molecules on bond strength (Turn 8). Jesse's dominance constrained the scope of conceptual exploration for Noah (Table 1).

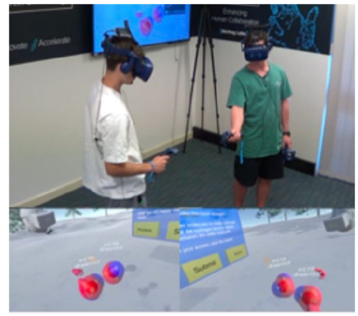
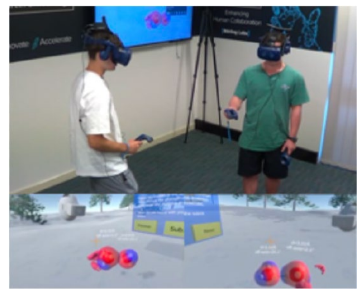
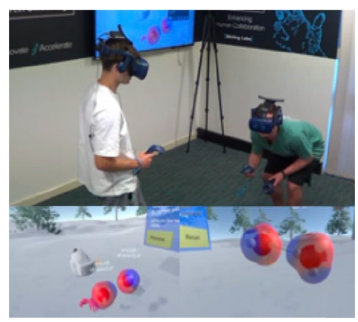
In terms of their physical movements, Noah and Jesse stood opposite each other and each stayed on a different side of the room as they explored ideas (refer to the synchronised video shots in Table 1). They did not walk around to observe the alignment between molecules from different directions, even though before iVR they had been given explicit instructions to walk around and change their perspectives. Instead, the students explored the virtual objects by rotating them. Even when Jesse lowered his body to observe the bond (Turn 8), it was only done for a brief moment, and he immediately went back to his initial posture.

Part 2: Students' Interactions with Conceptually Unfamiliar Objects

The focal task in the protein iVR activity required students to orient the substrate at the entrance of the enzyme for the catalytic reaction to occur. Before entering iVR, all students described enzymes as biological catalysts composed of amino acids. Most students (eight pairs) illustrated their ideas using simplistic diagrams explaining the lock-and-key mechanism (e.g., Fig. 3). These diagrams emphasised that the shape of the substrate needed to match that of the enzyme for the reaction to occur. Students also explained that enzyme reactions are very fast due to enzymes providing alternative pathways to reduce the energy required for the reaction. However, students were unable to explain precisely what the enzymes looked like or how they provided these alternative reaction pathways.

In protein iVR, students were surprised by the intricate enzyme structure, making remarks like "*Whoa, this thing is massive*". The structure starkly contrasted with their expectations from simple 2D diagrams. When prompted to orient the substrate molecule at the entrance of the enzyme, students initially stood outside the massive enzyme structure and attempted to orient the substrate molecule based on the most salient features. Five pairs focused on the shape of the passageway, intuitively applying the lock-and-key concept to push the substrate through and test the best fit. Three pairs recognised the red (electron-rich) regions at the entrance and oriented the substrate with its blue (electron-poor) end facing those red regions. The remaining two pairs observed that

Table 1 An excerpt of Jesse and Noah's interaction when exploring the nature of a hydrogen bond between two water molecules in snowflakes iVR

Turn	Speaker	Transcript	Synchronised video shots
	VR:	**How can you make this bond stronger? […]**	
1	*Jesse:*	I'm not really sure if we did it right. Because (*pause*) … or maybe we could try different places (*moves one of the molecules around the other; after several trials, a bond suddenly forms*). Oh, I did it. Okay, I think that's it	
2	*Noah:*	Yeah	*Turn 1: Jesse (green T-shirt) forms a hydrogen bond*
3	*Jesse:*	So, the bond is yellow for the previous question (pause) in relation to the… Okay, so… (*adjusts the distance between the molecules; Noah observes*) […]	
4	*Jesse:*	Is it, is it that? Do you wanna try rotating it like this? *(Gestures with the controller to show rotation then walks to move the molecules himself)*	
5	*Noah:*	*(surrenders control to Jesse)* Yeah, you got it	
6	*Jesse:*	*(manipulates the molecules)* Is it [hydrogen atom] reacting with this dot [the lone pair] here?	*Turn 3–5: Noah observes as Jesse continues to manipulate objects*
7	*Noah:*	Yeah, that one? Yeah	
8	*Jesse:*	Okay. That one goes green. And it's yellow … (*briefly lowers his body to observe the bond and then stands up*). Okay, so it looks like the further you go, it turns green, and then it becomes stronger	
9	*Noah:*	Yeah	*Turn 8: Jesse briefly lowers his body*

Video shots: Bottom left = Noah's view (white T-shirt); Bottom right = Jesse's view (green T-shirt)

inside the enzyme was mostly red (electron-rich). They initially oriented the substrate molecule with its blue (electron-poor) end entering the passageway first. Despite these initial differences, by looking at the complex enzyme structure, all student pairs recognised the importance of exploring the structure from different perspectives. During the interaction, students changed positions frequently to explore additional ideas. In addition, when encountering the resistance of the substrate at the entrance, students intuitively adjusted the angle of the molecule or tried different orientations.

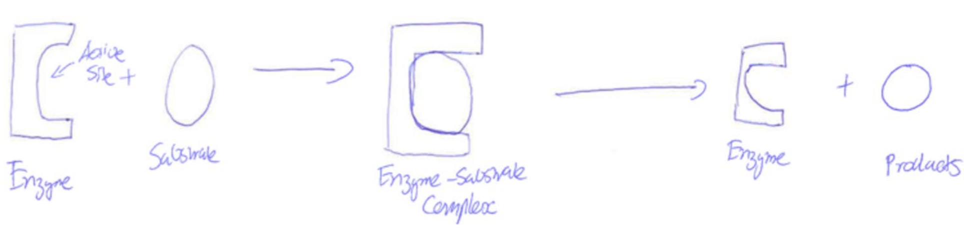


Fig. 3 An example of students' illustrations of an enzyme–substrate reaction before iVR

In terms of their collaboration, students worked closely to complete the task. The students perceived the task as one requiring the consideration of multiple concepts before settling on a solution. Among strangers, the unequal relations exhibited when exploring water molecules disappeared. These students took turns manipulating the substrate, freely shared and elaborated on ideas, and negotiated to reach a consensus. Pairs who were friends also maintained their collaborative dynamics.

The Case of Noah and Jesse Interacting with Conceptually Unfamiliar Virtual Objects

Before iVR, both students had heard about enzyme–substrate reactions. They described enzymes as entities that speed up reactions in biological systems by providing alternative pathways in which a lower amount of energy is required for those reactions to proceed. However, the students could not elaborate on this process further. In addition, both students exhibited uncertainty regarding the actual structure of enzymes. Jesse described an enzyme as "*a bunch of amino acids together*" while Noah described it as "*a long chain of amino acids*".

Inside iVR, both students were surprised when they first saw the complex structure of the enzyme. They also appeared unsure of the best way to approach the task. Therefore, they equally contributed to the generation and exploration of ideas, taking turns manipulating molecules, and elaborating on ideas. For example, when determining the best orientation of the substrate at the entrance of the enzyme, Jesse and Noah were at the enzyme entrance, observing the concrete shape of the enzyme passageway. Noah tried to fit the bulky (blue) end of the substrate in the narrow passageway to meet the red areas inside the enzyme, but his attempt was unsuccessful because he did not consider the shape of the passageway (Table 2, Turn 1). Jesse, focusing on the shape of the passageway, took over control and tested the fit of the substrate with its skinny (red) end entering the enzyme first (Turn 2). Despite Jesse's attempt being successful, Noah still focused on the (red) appearance of the walls inside the enzyme. Noah flipped the substrate and re-oriented it with the bulky (blue) end entering the passageway first (Turns 3–4). When Jesse emphasised the role of orientation (Turn 5), Noah explained his reasoning integrating his idea of the red regions inside the enzyme and Jesse's idea of the shape of the passageway (Turn 6). This extract shows how students narrated their actions and built on each other's ideas. When ideas diverged, students made efforts to reconcile by elaborating on what they were doing.

The synchronised video shots in Table 2 also show that Noah and Jesse frequently changed their positions during the interaction. Looking at the unfamiliar, complex structures of the enzyme and substrate, the students perceived that the task demanded more physical and conceptual exploration and that there could be multiple possibilities. As a result, the students did not settle for simple solutions but, instead, pushed the substrate multiple times to test its fit and explored the virtual environment extensively. These actions allowed the students to identify and integrate different chemistry concepts. For instance, while taking turns testing the fit of the substrate (Turns 1–6), Jesse realised that staying at the entrance limited his perspective. Therefore, he walked into the enzyme to explore more ideas. There, Jesse confirmed Noah's reasoning after observing red regions inside the enzyme (Turns 7–10). Jesse then went back to the entrance and oriented the molecule as originally suggested by Noah.

Discussion

In this study, we investigated how different learning tasks in different iVR contexts influenced students' collaborative interactions to learn abstract chemistry concepts. Our findings showed that students actively interacted with 3D objects in iVR to change their conceptual understanding. However, students' perceptions of the conceptual complexity of virtual objects prompted different physical, conceptual, and collaborative engagements while completing learning tasks in each iVR context.

Influence of the Nature of Learning Tasks on Students' Collaborative Interactions in iVR

In the iVR environment involving virtual objects that were conceptually familiar (water molecules), students perceived learning tasks as simple and engaged in short conceptual discussions and limited physical navigation. In contrast, when students encountered conceptually unfamiliar chemical structures (complex protein enzyme) in iVR, they recognised that there was no alternative way to explore such an object. Therefore, they engaged in exploratory embodied movements to fully appreciate the complex 3D structure. These findings were interesting considering that the molecular structures and their electron densities were represented similarly, and the target conceptual ideas were similar across the iVR learning activities. To form hydrogen bonds between water molecules, students needed to consider the composition and 3D shapes of water molecules, the attraction between oppositely charged (red and blue) areas, the role of lone pairs, and the distance and orientation between molecules. Similar considerations were needed to figure out the optimal orientation of the substrate molecule at the entrance of the enzyme. Based on our initial assessment, however, we expected that students would explore the virtual environment more actively for the water molecules task. This is because, without moving around and bending their knees

Table 2 An excerpt of Noah and Jesse's interaction while orienting the substrate at the entrance of the enzyme in protein iVR

Turn	Speaker	Transcript	Synchronised video shots
1	*Noah:*	I think like that (*orients the bulky end towards the tight-fit part of the passageway*) … it kind of fits up there… it said it was like a tight fit. So, maybe like that. Oh, no	
2	*Jesse:*	Let's try it this way. (*Flips the substrate, pushes it with the skinny end going in first*) So that's the only one that actually fits through (*pulls the substrate out*) […]	*Turn 2: Jesse (black T-shirt) pushes the substrate with the skinny end entering first*
3	*Jesse:*	Can you move this?	
4	*Noah:*	(*Flips the substrate; moves the bulky end to enter the enzyme first*)	
5	*Jesse:*	It needs to be at a particular angle. Ok?	
6	*Noah:*	(*Drops the molecule*) It has to be on a certain angle in order to attract like for the blue to attract the red kind of thing to be like kind of pulled in (*Looks at Jesse*)	*Turn 4: Noah takes control; flips and orients the substrate with the bulky end going in first*
7	*Jesse:*	um, and inside there's (*ducks and walks into the reaction site*) … a lot of red	
8	*Noah:*	A lot of red, yeah. So, I think the blue has to go in first and I think the angle just has to …	
9	*Jesse:*	(*Walks back to the entrance*)	*Turn 7: Jesse ducks and walks to experience the journey of the sustrate*
10	*Jesse:*	*(orients substrate with the bulky, blue end entering first)* … it looks like it will slot in (*lowers his body to peep inside the enzyme)* […]	

Video shots: Bottom left = Noah's view (grey T-shit); Bottom right = Jesse's view (black T-shirt)

in and out, students could not effectively evaluate the impact of orientation and the distance between water molecules and complete the task. On the other hand, less movement was anticipated for the substrate molecule orientation task; to complete the task, students could rely only on the features at the entrance of the enzyme – electron density and shape of the entrance – without necessarily walking around. Yet, because the enzyme molecule appeared conceptually unfamiliar, students felt that the learning tasks in protein iVR demanded different problem-solving skills compared to water molecules. The students were compelled to explore the enzyme environment and collaborate extensively.

Findings from the current study remind us that utilising and evaluating the educational affordances of iVR needs to coincide with the careful design of the learning activities. Indeed, there have been several calls to carefully utilise the unique affordances of iVR to support learning (e.g., Dalgarno & Lee, 2010; Mikropoulos & Natsis, 2011). However, common iVR applications for science learning presented concepts (e.g., shapes of molecules as in Brown et al., 2021; Edwards et al., 2019; Fujiwara et al., 2020) that are easily accessible through existing media. These applications did not effectively utilise the unique value of iVR for 3D visualisation, but research studies tended to evaluate the educational benefits of iVR based on such iVR applications. Our findings in terms of the limited nature of students' interactions while exploring such simple and conceptually familiar objects in iVR could potentially explain why iVR was not superior to alternative media in terms of students' learning (e.g., Brown et al., 2021). To encourage students' exploratory interactions with concepts in iVR, interactive objects need to highlight the benefit of 3D visualisation in iVR which cannot otherwise be achieved.

Regarding students' social dynamics, previous studies have emphasised the influence of group composition on students' collaborative learning behaviours (e.g., Ungu et al., 2023d; Janssen et al., 2009; Webb, 1991; Webb et al., 1998). For instance, students tend to be less critical of contributions made by unfamiliar peers (Janssen et al., 2009) and adopt expert-novice relations when they perceive a big gap in their abilities (Webb, 1991). Students also relied more on the information provided by their collaborators when they perceived these peers as more competent (Andrews & Rapp, 2014). Our findings in the present study were consistent with these observations but only when students explored conceptually familiar objects in iVR (e.g., two water molecules in snowflake iVR). When students encountered complex, unfamiliar structures in iVR (e.g., the entrance of enzyme in protein iVR), students perceived learning tasks as complex and prior unbalanced relations were modified.

Our findings suggest that, in iVR, the design of virtual objects and learning tasks influences students' tendencies to collaborate with peers. Therefore, to encourage students' collaborative interactions in iVR, learning tasks need to be designed so that the solutions are not so simple for individual students to accomplish without input from peers. This conclusion resonates with prior research on the impact of task design on students' collaborative interactions (e.g., Chizhik, 2001; Cohen, 1994; Esmonde, 2009; Kirschner et al., 2004). Generally, tasks that no single individual feels sufficiently equipped to complete successfully alone elicit more student interactions than tasks that appear manageable to individuals (Care et al., 2015; Cohen et al., 1999; Scager et al., 2016). Even unfamiliar peers are forced to share resources, utilise each other's ideas, and facilitate each other's efforts (Cohen et al., 1999).

Affordances of Collaborative iVR for Learning Chemistry Concepts

The designed iVR environments showed concrete structures of molecules, such as the protein enzyme, and challenged students' imagination of the structures. In addition, the interactivity and embodied interactions with virtual objects supported by iVR gave students a sense of control over their learning and enhanced their comprehension of the target concepts (Johnson-Glenberg, 2018). By testing possibilities and observing consequences, students modified their conceptions of molecular interactions—for example, hydrogen bond formation in relation to orientation and distance of molecules; and influence of molecular structure and electron density in enzyme–substrate reactions. Moreover, the collaborative design allowed students to negotiate ideas and complement each other's spatial and conceptual perspectives. Our study lends support to research that suggests that interactive and collaborative iVR helps students visualise abstract science concepts and actively construct knowledge (Matovu et al., 2023b; Chen, 2010; Johnson-Glenberg, 2018; Salzman et al., 1999).

Theoretical Contribution and Limitations of this Study

The present study showcases the unique capacity of iVR to engage students in exploring, problem-solving, and comprehending the complex 3D nature of chemical interactions, such as hydrogen bonds and enzyme–substrate reactions. Students were able to interact with otherwise abstract chemistry ideas in concrete forms to test their ideas and learn. In addition, most studies rely on pre-and post-tests to demonstrate the value of iVR, report individual students' experiences with iVR (e.g., Lui et al., 2020), or describe students' collaboration when one is using iVR and the other a 2D platform (e.g., Price et al., 2020; Uz-Bilgin et al., 2020). In contrast, the present study documents students' collaborative interactions and meaning-making processes when both students are present in the same iVR learning environment. In essence, the study highlights a paradigm shift in the conceptualisation and application of iVR in education, positioning it as a transformative medium to support collaborative learning experiences. Importantly, the study demonstrates the need for carefully crafted learning tasks in collaborative iVR contexts. The study, therefore, provides insights into how iVR-based learning tasks can be leveraged to promote collaborative learning interactions. At the same time, the study also demonstrates the importance of using synchronised videos and multimodal transcripts in analysing such students' interactions. Future studies may wish to adopt a similar approach to analyse students' interactions.

Nevertheless, the study suffered from some limitations. Firstly, this research was conducted in a very specific educational context (undergraduate chemistry) which may limit the generalisability of the findings. Educators may want to further explore students' collaborative interactions in iVR in other educational contexts and with different learning content.

Secondly, students in the present study completed three iVR activities, starting with the snowflake iVR and ending with protein iVR. The students might have become more comfortable exploring virtual spaces and interacting with peers as they reached the last iVR activity (protein iVR). This familiarity with peers and the iVR environments can be a confounding variable in understanding the role of the complexity of virtual objects in students' interactions. Future studies may wish to change the order of the learning activities to isolate the effects of familiarity and complexity of virtual objects. This interplay of familiarity with iVR and with peers, the nature of iVR context, and perceived task complexity in our study highlights the complexity of analysing students' collaborative interactions in iVR.

In addition, the study reported here did not investigate how the nature of molecular representations used in iVR influenced students' interactions and learning. Chemical representations can vary in many ways, for example in terms of what molecular entities, properties, or attributes are represented, and what qualitative or quantitative information can be inferred (Talanquer, 2022). The molecular representations used in our iVR applications highlighted the particulate and electronic aspects of molecules, with emphasis on molecular size and shape, and electron densities. Changing the nature of representations to highlight different aspects might influence how students interact with, reason about, and make meaning from the representations (Talanquer, 2022). The present study, thus, paves the way for future researchers who may wish to investigate how different molecular representations could influence students' interactions and learning.

Furthermore, the present study did not thoroughly delve into the conceptual benefits and limitations of iVR. These aspects have been addressed in separate manuscripts. For instance, a prior study from our research team found that iVR helped most of the students to recognise the intermolecular nature of hydrogen bonds, the role of lone pairs of electrons in forming hydrogen bonds, and the 3D nature of hydrogen bonds (Matovu et al., 2023b). However, a future study showing the direct relationship between students' collaborative interactions in iVR, and their pre-/post-test scores could offer further insights into the specific interactions that fostered distinct kinds of learning.

Conclusions

In this study, we designed multiple chemistry learning activities in iVR and investigated how students' perceptions of the complexity of learning tasks in different iVR contexts influenced their collaborative interactions. Utilising 3D visualisation, interactivity, embodied movements, and collaboration features of iVR helped students construct new understandings of molecular interactions. However, students' engagement in physical, conceptual, and collaborative exploration differed depending on the perceived complexity of virtual objects. This study shows that, although iVR programs for learning are designed with similar design features (such as interactivity, embodied movements, or collaboration), not all tasks can optimise collaborative interactions from learners. Only the tasks that highlighted the unique value of 3D visualisation in iVR – embodied exploration of complex 3D structures – prompted extensive interactions from students. To realise the educational benefits of iVR for science learning, educators need to pay careful attention to the design of interactive tasks in iVR.

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Data Availability Following the research ethics guidelines, the data won't be made available.

Declarations

Ethics Declaration Participation in the study was voluntary. The institutional research ethics committee granted permission to conduct this study (HRE2020-0081) and all participants signed consent forms. Any identifying information was also removed from the data during analysis and reporting. For instance, pseudonyms were used instead of students' actual names.

Competing Interests There are no known competing interests to declare.

References

Andrews, J. J., & Rapp, D. N. (2014). Partner characteristics and social contagion: Does group composition matter? *Applied Cognitive Psychology, 28*(4), 505–517. https://doi.org/10.1002/acp.3024

Barreda-Ángeles, M., Horneber, S., & Hartmann, T. (2023). Easily applicable social virtual reality and social presence in online higher education during the covid-19 pandemic: A qualitative study. *Computers & Education: X Reality, 2*, 100024. https://doi.org/10.1016/j.cexr.2023.100024

Barron, B. (2003). When smart groups fail. *Journal of the Learning Sciences, 12*(3), 307–359. https://doi.org/10.1207/S15327809JLS1203_1

Brown, C. E., Alrmuny, D., Williams, M. K., Whaley, B., & Hyslop, R. M. (2021). Visualizing molecular structures and shapes: A comparison of virtual reality, computer simulation, and traditional modeling. *Chemistry Teacher International, 3*(1), 69–80. https://doi.org/10.1515/cti-2019-0009

Care, E., Griffin, P., Scoular, C., Awwal, N., & Zoanetti, N. (2015). Collaborative problem solving tasks. In P. Griffin & E. Care (Eds.), *Assessment and teaching of 21st century skills: Methods and approach* (pp. 85–104). Springer. https://doi.org/10.1007/978-94-017-9395-7_4

Chen, C. J. (2010). Theoretical bases for using Virtual Reality in education. *Themes in Science and Technology Education*, *2*(1–2), 71–90. http://earthlab.uoi.gr/ojs/theste/index.php/theste/article/view/23

Chizhik, A. W. (2001). Equity and status in group collaboration: Learning through explanations depends on task characteristics. *Social Psychology of Education, 5*(2), 179–200. https://doi.org/10.1023/A:1014405118351

Cohen, E. G. (1994). Restructuring the classroom: Conditions for productive small groups. *Review of Educational Research, 64*(1), 1–35. https://doi.org/10.3102/00346543064001001

Cohen, E. G., Lotan, R. A., Scarloss, B. A., & Arellano, A. R. (1999). Complex instruction: Equity in cooperative learning classrooms. *Theory into Practice, 38*(2), 80–86. https://doi.org/10.1080/00405849909543836

Cowan, K. (2014). Multimodal transcription of video: Examining interaction in early years classrooms. *Classroom Discourse, 5*(1), 6–21. https://doi.org/10.1080/19463014.2013.859846

Dalgarno, B., & Lee, M. J. (2010). What are the learning affordances of 3-D virtual environments? *British Journal of Educational Technology, 41*(1), 10–32. https://doi.org/10.1111/j.1467-8535.2009.01038.x

Dede, C. (2009). Immersive interfaces for engagement and learning. *Science, 323*(5910), 66–69. https://doi.org/10.1126/science.1167311

Edwards, B. I., Bielawski, K. S., Prada, R., & Cheok, A. D. (2019). Haptic virtual reality and immersive learning for enhanced organic chemistry instruction. *Virtual Reality, 23*, 363–373. https://doi.org/10.1007/s10055-018-0345-4

Esmonde, I. (2009). Mathematics learning in groups: Analyzing equity in two cooperative activity structures. *Journal of the Learning Sciences, 18*(2), 247–284. https://doi.org/10.1080/10508400902797958

Fujiwara, D., Kellar, K., Humer, I., Pietroszek, K., & Eckhardt, C. (2020). VSEPR theory, an interactive and immersive virtual reality. In D. Economou, A. Klippel, H. Dodds, A. Peña-Rios, M. J. W, D. Beck, J. Pirker, A. Dengel, T. M. Peres, & J. Richter (Eds.), *Proceedings of 6th international conference of the Immersive Learning Research Network (iLRN)* (pp. 140–146). IEEE. https://doi.org/10.23919/iLRN47897.2020.9155185

Glaser, B. G. (1965). The constant comparative method of qualitative analysis. *Social Problems, 12*(4), 436–445. https://doi.org/10.2307/798843

Graesser, A. C., Fiore, S. M., Greiff, S., Andrews-Todd, J., Foltz, P. W., & Hesse, F. W. (2018). Advancing the science of collaborative problem solving. *Psychological Science in the Public Interest, 19*(2), 59–92. https://doi.org/10.1177/1529100618808244

Hakkarainen, K., Paavola, S., Kangas, K., & Seitamaa-Hakkarainen, P. (2013). Toward collaborative knowledge creation. In C. E. Hmelo-Silver, C. A. Chinn, C. K. K. Chan, & A. O'Donnell (Eds.), *International handbook of collaborative learning* (pp. 57–73). Routledge. https://doi.org/10.4324/9780203837290

Han, E., Miller, M. R., DeVeaux, C., Jun, H., Nowak, K. L., Hancock, J. T., Ram, N., & Bailenson, J. N. (2023). People, places, and time: a large-scale, longitudinal study of transformed avatars and environmental context in group interaction in the metaverse. *Journal of Computer-Mediated Communication, 28*(2), zmac031. https://doi.org/10.1093/jcmc/zmac031

Huang, W., Roscoe, R. D., Johnson-Glenberg, M. C., & Craig, S. D. (2021). Motivation, engagement, and performance across multiple virtual reality sessions and levels of immersion. *Journal of Computer Assisted Learning, 37*(3), 745–758. https://doi.org/10.1111/jcal.12520

Janssen, J., Erkens, G., Kirschner, P. A., & Kanselaar, G. (2009). Influence of group member familiarity on online collaborative learning. *Computers in Human Behavior, 25*(1), 161–170. https://doi.org/10.1016/j.chb.2008.08.010

Jewitt, C. (2013). Multimodal methods for researching digital technologies. In S. Price, C. Jewitt, & B. Brown (Eds.), *The SAGE handbook of digital technology research* (pp. 250–265). SAGE. https://doi.org/10.4135/9781446282229.n18

Johnson-Glenberg, M. C. (2018). Immersive VR and education: Embodied design principles that include gesture and hand controls. *Frontiers in Robotics and AI, 5*, 81. https://doi.org/10.3389/frobt.2018.00081

Kirschner, P., Strijbos, J.-W., Kreijns, K., & Beers, P. J. (2004). Designing electronic collaborative learning environments. *Educational Technology Research and Development, 52*(3), 47–66. https://doi.org/10.1007/BF02504675

Kirschner, P. A., Beers, P. J., Boshuizen, H. P. A., & Gijselaers, W. H. (2008). Coercing shared knowledge in collaborative learning environments. *Computers in Human Behavior, 24*(2), 403–420. https://doi.org/10.1016/j.chb.2007.01.028

Kreijns, K., Kirschner, P. A., & Jochems, W. (2003). Identifying the pitfalls for social interaction in computer-supported collaborative learning environments: A review of the research. *Computers in Human Behavior, 19*(3), 335–353. https://doi.org/10.1016/S0747-5632(02)00057-2

Kreijns, K., Xu, K., & Weidlich, J. (2022). Social presence: Conceptualization and measurement. *Educational Psychology Review, 34*(1), 139–170. https://doi.org/10.1007/s10648-021-09623-8

Lipponen, L., Rahikainen, M., Lallimo, J., & Hakkarainen, K. (2003). Patterns of participation and discourse in elementary students' computer-supported collaborative learning. *Learning and Instruction, 13*(5), 487–509. https://doi.org/10.1016/S0959-4752(02)00042-7

Lui, M., McEwen, R., & Mullally, M. (2020). Immersive virtual reality for supporting complex scientific knowledge: Augmenting our understanding with physiological monitoring. *British Journal of Educational Technology, 51*(6), 2180–2198. https://doi.org/10.1111/bjet.13022

Makransky, G., Wismer, P., & Mayer, R. E. (2019). A gender matching effect in learning with pedagogical agents in an immersive virtual reality science simulation. *Journal of Computer Assisted Learning, 35*(3), 349–358. https://doi.org/10.1111/jcal.12335

Malmberg, J., Haataja, E., & Järvelä, S. (2022). Exploring the connection between task difficulty, task perceptions, physiological arousal and learning outcomes in collaborative learning situations. *Metacognition and Learning, 17*(3), 793–811. https://doi.org/10.1007/s11409-022-09320-z

Maloney, D., & Freeman, G. (2020). Falling asleep together: What makes activities in social virtual reality meaningful to users. In P. Mirza-Babaei, V. McArthur, V. V. Abeele, & M. Birk (Eds.), *Proceedings of the annual symposium on computer-human interaction in play* (pp. 510–521). Association for Computing Machinery. https://doi.org/10.1145/3410404.3414266

Matovu, H., Ungu, D. A. K., Won, M., Tsai, C.-C., Treagust, D. F., Mocerino, M., & Tasker, R. (2023a). Immersive Virtual Reality for science learning: Design, implementation, and evaluation. *Studies in Science Education, 59*(2), 205–244. https://doi.org/10.1080/03057267.2022.2082680

Matovu, H., Won, M., Treagust, D. F., Ungu, D. A. K., Mocerino, M., Tsai, C.-C., & Tasker, R. (2023b). Change in students' explanation of the shape of snowflakes after collaborative immersive virtual reality. *Chemistry Education Research and Practice, 24*(2), 509–525. https://doi.org/10.1039/D2RP00176D

Mikropoulos, T. A., & Natsis, A. (2011). Educational virtual environments: A ten-year review of empirical research (1999–2009). *Computers & Education, 56*(3), 769–780. https://doi.org/10.1016/j.compedu.2010.10.020

Oh, C. S., Bailenson, J. N., & Welch, G. F. (2018). A systematic review of social presence: Definition, antecedents, and implications. *Frontiers in Robotics and AI, 5*, 114. https://doi.org/10.3389/frobt.2018.00114

Pande, P., Thit, A., Sørensen, A. E., Mojsoska, B., Moeller, M. E., & Jepsen, P. M. (2021). Long-term effectiveness of immersive VR simulations in undergraduate science learning: Lessons from a media-comparison study. *Research in Learning Technology*. https://doi.org/10.25304/rlt.v29.2482

Price, S., Yiannoutsou, N., & Vezzoli, Y. (2020). Making the body tangible: Elementary geometry learning through VR. *Digital Experiences in Mathematics Education, 6*(2), 213–232. https://doi.org/10.1007/s40751-020-00071-7

Qin, T., Cook, M., & Courtney, M. (2021). Exploring chemistry with wireless, PC-less portable Virtual Reality laboratories. *Journal of Chemical Education, 98*(2), 521–529. https://doi.org/10.1021/acs.jchemed.0c00954

Radianti, J., Majchrzak, T. A., Fromm, J., & Wohlgenannt, I. (2020). A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda. *Computers & Education, 147*, 103778. https://doi.org/10.1016/j.compedu.2019.103778

Ripka, G., Grafe, S., & Latoschik, M. E. (2020). Preservice teachers' encounter with Social VR – Exploring virtual teaching and learning processes in initial teacher education. In E. Langran (Ed.), *Proceedings of SITE interactive 2020 online conference* (pp. 549–562). Association for the Advancement of Computing in Education (AACE). https://www.learntechlib.org/p/218201

Roschelle, J., & Teasley, S. D. (1995). The construction of shared knowledge in collaborative problem solving. In C. O'Malley (Ed.), *Computer supported collaborative learning* (pp. 69–97). Springer. https://doi.org/10.1007/978-3-642-85098-1_5

Salzman, M. C., Dede, C., Loftin, R. B., & Chen, J. (1999). A model for understanding how virtual reality aids complex conceptual learning. *Presence: Teleoperators and Virtual Environments, 8*(3), 293–316. https://doi.org/10.1162/105474699566242

Šašinka, Č, Stachoň, Z., Sedlák, M., Chmelík, J., Herman, L., Kubíček, P., Šašinková, A., Doležal, M., Tejkl, H., & Urbánek, T. (2019). Collaborative immersive virtual environments for education in geography. *ISPRS International Journal of Geo-Information, 8*(1), 3. https://doi.org/10.3390/ijgi8010003

Scager, K., Boonstra, J., Peeters, T., Vulperhorst, J., & Wiegant, F. (2016). Collaborative learning in higher education: Evoking positive interdependence. *CBE—Life Sciences Education, 15*(4), ar69. https://doi.org/10.1187/cbe.16-07-0219

Slater, M., & Sanchez-Vives, M. V. (2016). Enhancing our lives with immersive virtual reality. *Frontiers in Robotics and AI, 3*, 74. https://doi.org/10.3389/frobt.2016.00074

Southgate, E., Smith, S. P., Cividino, C., Saxby, S., Kilham, J., Eather, G., Scevak, J., Summerville, D., Buchanan, R., & Bergin, C. (2019). Embedding immersive virtual reality in classrooms: Ethical, organisational and educational lessons in bridging research and practice. *International Journal of Child-Computer Interaction, 19*, 19–29. https://doi.org/10.1016/j.ijcci.2018.10.002

Talanquer, V. (2022). The complexity of reasoning about and with chemical representations. *JACS Au, 2*(12), 2658–2669. https://doi.org/10.1021/jacsau.2c00498

Ungu, D. A. K., Won, M., Treagust, D. F., Mocerino, M., Matovu, H., Tsai, C.-C., & Tasker, R. (2023). Students' use of magnetic models to learn hydrogen bonding and the formation of snowflakes. *Journal of Chemical Education, 100*(7), 2504–2519. https://doi.org/10.1021/acs.jchemed.2c00697

Uz-Bilgin, C., Thompson, M., & Anteneh, M. (2020). Exploring how role and background influence through analysis of spatial dialogue in collaborative problem-solving games. *Journal of Science Education and Technology, 29*, 813–826. https://doi.org/10.1007/s10956-020-09861-5

Vygotsky, L. S. (1978). *Mind in society: The development of higher psychological processes*. Harvard University Press.

Walkington, C., Nathan, M. J., Huang, W., Hunnicutt, J., & Washington, J. (2023). Multimodal analysis of interaction data from embodied education technologies. *Educational Technology Research and Development*. https://doi.org/10.1007/s11423-023-10254-9

Webb, M., Tracey, M., Harwin, W., Tokatli, O., Hwang, F., Johnson, R., Barrett, N., & Jones, C. (2022). Haptic-enabled collaborative learning in virtual reality for schools. *Education and Information Technologies, 27*(1), 937–960. https://doi.org/10.1007/s10639-021-10639-4

Webb, N. M. (1991). Task-related verbal interaction and mathematics learning in small groups. *Journal of Research in Mathematics Education, 22*(5), 366–389. https://doi.org/10.5951/jresematheduc.22.5.0366

Webb, N. M. (2009). The teacher's role in promoting collaborative dialogue in the classroom. *British Journal of Educational Psychology, 79*(1), 1–28. https://doi.org/10.1348/000709908X380772

Webb, N. M. (2013). Information processing approaches to collaborative learning. In C. E. Hmelo-Silver, C. A. Chinn, C. K. K. Chan, & A. O'Donnell (Eds.), *The international handbook of collaborative learning* (pp. 19–40). Routledge. https://doi.org/10.4324/9780203837290

Webb, N. M., Nemer, K. M., Chizhik, A. W., & Sugrue, B. (1998). Equity issues in collaborative group assessment: Group composition and performance. *American Educational Research Journal, 35*(4), 607–651. https://doi.org/10.3102/00028312035004607

Won, M., Mocerino, M., Tang, K.-S., Treagust, D. F., & Tasker, R. (2019). Interactive immersive virtual reality to enhance students' visualisation of complex molecules. In M. Schultz, S. Schmid, & G. A. Lawrie (Eds.), *Research and practice in chemistry education* (pp. 51–64). Springer. https://doi.org/10.1007/978-981-13-6998-8_4

Won, M., Ungu, D. A. K., Matovu, H., Treagust, D. F., Tsai, C.-C., Park, J., Mocerino, M., & Tasker, R. (2023). Diverse approaches to learning with immersive Virtual Reality identified from a systematic review. *Computers & Education, 195*, 104701. https://doi.org/10.1016/j.compedu.2022.104701

Wu, H.-K., & Shah, P. (2004). Exploring visuospatial thinking in chemistry learning. *Science Education, 88*(3), 465–492. https://doi.org/10.1002/sce.10126

Zhang, X., Meng, Y., Ordóñez de Pablos, P., & Sun, Y. (2019). Learning analytics in collaborative learning supported by Slack: From the perspective of engagement. *Computers in Human Behavior, 92*, 625–633. https://doi.org/10.1016/j.chb.2017.08.012