STEREOISOMERS, NOT STEREO ENIGMAS: A STEREOCHEMISTRY ESCAPE ACTIVITY INCORPORATING AUGMENTED AND IMMERSIVE VIRTUAL REALITY

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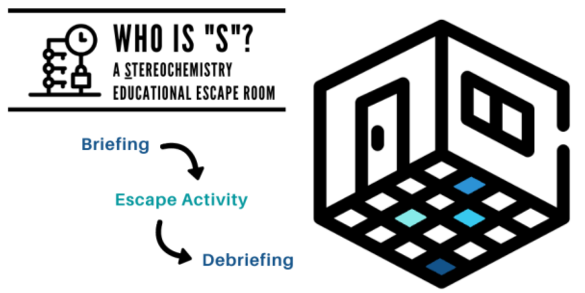
ABSTRACT

An educational escape activity was developed, embedding elements of both augmented and immersive virtual reality technologies, in an active learning environment. The mental visualization of abstract concepts can be difficult for students, inhibiting their ability to reason cogently regarding important topics of stereochemistry. Consequently, an educational escape room coupled with immersive technologies can be utilized to foster teamwork and critical thinking while encouraging student interaction with three-dimensional virtual molecular phenomena. Nine participants were recruited from the University of East Anglia to complete the activity. From this first experience, student feedback and subsequent thematic analysis show not only the significant positive impacts on student engagement and learning but also the potential of this paradigm to be adopted as an educational tool.

GRAPHICAL ABSTRACT



KEYWORDS

First-Year Undergraduate/General, Collaborative/Cooperative Learning, Humor/Puzzles/Games, Computer-Based Learning, Problem Solving/Decision Making, Stereochemistry

Students are learners who construct their own understanding and knowledge of the world, based on their own unique experiences. This is one of the core principles of constructivism, most famously voiced by Dewey and Piaget, that learner engagement with the world subsequently constructs meaning through sensory input. Although this predominantly occurs within the mind, there is a necessity to provide learning environments which engage physically as well as mentally. Dewey referred to this as reflective thinking.[1]

Consequently, education researchers are increasingly adopting game-based learning (GBL), the integration of game technologies into learning experiences, to increase engagement and promote situated experiential learning.[2] In contrast to more traditional didactic styles of teaching, GBL can be targeted appropriately to the skill level of individual learning. This often results in effective focus on a task, resulting in deep learning and high levels of satisfaction.[3]

The difficulty students exhibit in understanding abstract concepts,[4–6] including but not limited to the field of stereochemistry,[7] is widely reported in chemistry education research. In relation to these concepts, metaphors such as the triangle model developed by Johnstone[8]—expanded upon by Mahaffy[9]—describes how the “expert” chemist moves between different levels of chemistry: microscopic, macroscopic, symbolic, and human association with chemical processes. However, for students of chemistry this can be difficult.

The cognitive challenges of visualizing three-dimensional molecular phenomena are frequently reported as a demanding task for students, inhibiting their ability to reason cogently regarding important topics of stereochemistry. This can leave students feeling frustrated and demotivated. The transition from two-dimensional images to three-dimensional constructs is neither natural nor easy[10] and arguably, students currently have insufficient interaction with three-dimensional objects of this nature.[11] Exposure to three-dimensional interactive media within virtual reality learning environments (VRLE) is one teaching technique utilized to encourage student interaction with dynamic 3-D molecular objects.[12–14]

Within chemistry education, a VRLE offers opportunities for students to interact with representations of scientific phenomena which could not be perceived in the physical world. This is achieved through the use of immersive virtual reality (iVR) to engage an individual within a computer-generated environment through the use of a head-mounted display (HMD). HMDs detect the users' head motion throughout the experience, constantly updating the displayed graphics to reflect the changing viewpoint.[15] Recent developments include a Virtual Reality Multisensory Classroom (VRMC) employing haptic feedback for building molecules,[4] an interactive virtual environment visualizing real-time molecular dynamics (iMD-VR)[16] and a virtual environment for teaching enzyme catalysis.[17] These hardware/software technologies allow individuals to interactively manipulate and navigate high fidelity scientific representations; experiences that cannot be obtained in other ways.

A second approach, augmented reality (AR), provides a seamless interface for users that combines both the real world and the virtual world. In contrast to virtual reality (VR), users interact with virtual objects that are superimposed on real environments surrounding the observer and provide the most natural and genuine human-computer interaction experience.[18] As AR becomes more widely available to educational researchers, the advantages and pedagogical affordances of integrating this technology into the learning of abstract subject material such as submicroscopic concepts are increasingly reported.[18,19]

A key pedagogical affordance of interactive digital media such as AR and iVR is the ability to rotate and translate virtual objects, allowing students a better understanding of spatial concepts through manipulation of the properties and relationships of objects that would be either too small or too large to examine effectively in a non-virtual environment. By using AR, in a way that encourages students to engage on a deeper level, students can make deep and lasting connections within their knowledge base.[20,21]

EDUCATIONAL ESCAPE ROOMS

Educational escape rooms have emerged as a paradigm to engage students in active learning through an immersive environment that promotes teamwork and problem solving to achieve a mutual goal. Groups of participants work collaboratively to escape the room before the timer expires. This is achieved by solving a series of puzzles, related to the narrative theme of the room. Hints are provided when necessary, to ensure that participants remain on track to complete the activity within the allotted time. At the end of the escape room, participants are led through a debriefing process.

Escape rooms require teamwork, communication, as well as critical thinking, attention to detail and lateral thinking.[22] Previous meta-analysis of research studies demonstrate that greater engagement subsequently results in increased student learning.[23] Active learning requires students to participate unlike previous paradigms such as didactic teaching where responsibility rested with the instructor and the learner played a passive, receptive role.

Due to international success as a recreational activity, escape rooms are being increasingly adopted by education researchers seeking to increase student motivation and enhance social problem-solving skills.[24–29] Yet, despite emerging examples of educational escape rooms, few studies have focused on higher education chemistry. Previously reported educational escape activities have been outlined in Table 1, alongside further information regarding the incorporated game mechanics and chemistry topics covered. Gamified learning initiatives around the topic of stereochemistry have also been reported previously[30–33] but no educational escape activities around topics of stereochemistry in inorganic chemistry exist in the literature, with minimal studies incorporating the use of augmented and virtual reality technologies. Herein, we describe the development of an escape room activity (with embedded AR/iVR) for evaluating higher education chemistry students' understanding of topics of stereochemistry. In addition, students' perceptions of the learning effectiveness of both the escape activity and the utilization of technologies such as AR and iVR in understanding concepts of stereochemistry are also reported.

Table 1. Synopsis of previously published Educational Escape Activities for Higher Education Chemistry

Authors (Year)	Purpose of Escape Activity	Participants	Escape Room Activity and Game Mechanics	Success Rate	iVR or AR Used?
Ferreiro-González et al. (2019)[a]	Escape ClassRoom "CSI: 1.0": An interactive analytical chemistry escape activity for evaluating students at the end of the subject	43 students	Scenario 1: The Scientific Police Station, Adaptation Zone (Introduce players to the game's plot; Players obtain a secret code to open a locked case and safe-deposit box containing equipment required to complete the activity); Scenario 2: The Crime Scene, Sampling Zone (Evidence collection and application of the sampling procedure); Scenario 3: The Forensic Laboratory, Experimental Analysis, Data Treatment, and Interpretation of the Results (Sample analysis: Toxicological, Chromatography-mass spectrometry, audiovisual, and fingerprinting; Correct analysis provided the final code)	50% of teams escaped in time	No
Vergne et al. (2019)[b]	Laboratory Escape Activity: An escape room activity introduced to foster team building and collaborative learning in a laboratory-experiment setting	Two groups of ~15 students	Obtaining a secret code to access equipment needed to complete the activity; Use of different analytical techniques: UV-Vis, GC-MS, FT-IR; Solving a riddle based on the periodic table	Students finished with times in the range of 35–55 min	No
Clapson et al. (2020)[c]	ChemEscape: To engage and have participants enhance and apply discipline specific skills and knowledge	800 engineering students	The solution to each puzzle is a set of three numbers: Puzzle 1, Thin Layer Chromatography; Puzzle 2, Buoyancy Bottle; Puzzle 3, Density Tower; Puzzle 4: Zinc/Copper Water Cell	~60% escaped	No
Estudante and Dietrich (2020)[d]	Two scenarios: The LeBlanc process, a physical escape activity (previously published in 2018); The Solway process, an AR escape room application to diffuse AR to a large audience	>70 volunteers	Puzzle 1: an easy puzzle based on the periodic table; Puzzle 2: Finding a molecule for which the CPK color representation is close to the flag of Belgium; Puzzle 3: Compound identification (writing chemical formulas); Puzzle 4: Obtaining a code from global equation of the Solway process	95% escaped	AR used
Vergne et al. (2020)[e]	ESCAPE from the Chocolate Factory: Online virtual escape room game for an undergraduate chemistry lab class	8 students	Overall game description using video media; Roaster Room: Determination of molecular weight (with visual aid); Chocolate Processing Room: pH problem with video; Packaging Room: Matching of chromatography terms; Gift Shop: Linear regression problem with video	Students finished with times in the range of 10–20 min	No
Ang et al. (2020)[f]	Online virtual escape room to reinforce concepts of chemical bonding	24 students completed the physical escape room	Puzzle 1: Determination of net dipole moment in molecules; Puzzle 2: Strengths of different chemical bonds and molecular interactions; Puzzle 3: Bond strengths of metallic, covalent, and ionic bonds; Puzzle 4: To teach terminology relevant to chemical bonding; Final puzzle: Determination of the presence and comparison of the strength of hydrogen bonds in molecules	Not explicitly stated	No

[a]See ref *24*. [b]See ref *25*. [c]See ref *26*. [d]See ref *27*. [e]See ref *28*. [f]See ref *29*.

EXPERIMENTAL DESIGN AND PARTICIPANTS

The School of Chemistry at the University of East Anglia (UEA) is a dual-intensive (research and teaching) department delivering bachelors and integrated masters degrees in chemistry. The participant cohort identified for this research study were first year undergraduate students currently enrolled in the module "Bonding, Structure and Periodicity", a compulsory module of inorganic and general chemistry study, for academic year 2019–2020. Ethical approval was obtained for the evaluative aspect of the research study, and informed consent was obtained from all participants. Participants were randomly assigned to one of three research groups to avoid bias and confounding variables associated with the selection of participants:

- **Experimental group 1** whose escape activity incorporated physical molecular modelling kits. This group was treated as the control throughout the study.
- **Experimental group 2** whose escape activity incorporated the AR tool.
- **Experimental group 3** whose escape activity incorporated the iVR tool.

Each group participated in only one escape activity to eliminate carryover effects. A lecture on stereochemistry topics was conducted with the student cohort prior to the activity. Experimental groups 2 and 3 were provided with a short introductory session on how to appropriately operate the AR and iVR technologies to ensure sufficient competency to complete the activity. A health screening questionnaire was circulated to participants utilizing the iVR system before and after the escape activity.[34] The questionnaire has 16 questions[35] and is available in the Supporting Information.

ESCAPE ROOM DESIGN

The educational objective of the study was to develop an escape room learning environment to reinforce topics of stereochemistry and develop soft skills such as communication and teamwork. An important initial aspect of escape room design is the creation of an interesting narrative, where the puzzles are part of the storytelling and help progress the activity. In a commercial setting, these puzzles require no specialized knowledge or skill, with popular puzzle types including “searching for physical objects hidden in a room”, “symbol substitution with a key”, and “assembly of a physical object”.[22] For educational escape rooms, the challenge thus evolves to constructing puzzles that both fit the chosen narrative, but also sufficiently incorporate the key competencies of the teaching material.

The narrative of the activity was based on the recruitment of participants into a fictional secret intelligence agency. An individual, denoted throughout the activity as “S”, has left secret intel highly valued by the agency. However, this intel has been securely encrypted, and to ensure the information remains secure, the decryption passkeys that provide access to this intel will be permanently deleted one hour after being first viewed. As the passkeys were chemistry-based, the narrative dictated that their skill set was uniquely identified by the agency for this task.

Pre-allocated hints are provided as an attempt to ensure that teams progress at a rate sufficient for participation in all aspects of the educational activity within the allotted time. The adoption of an educational escape room was prompted by the escapED framework.[36] As per the escapED framework, six main areas were considered while developing the study: Participants, Objectives, Theme, Puzzles, Equipment and Evaluation (Figure 1).

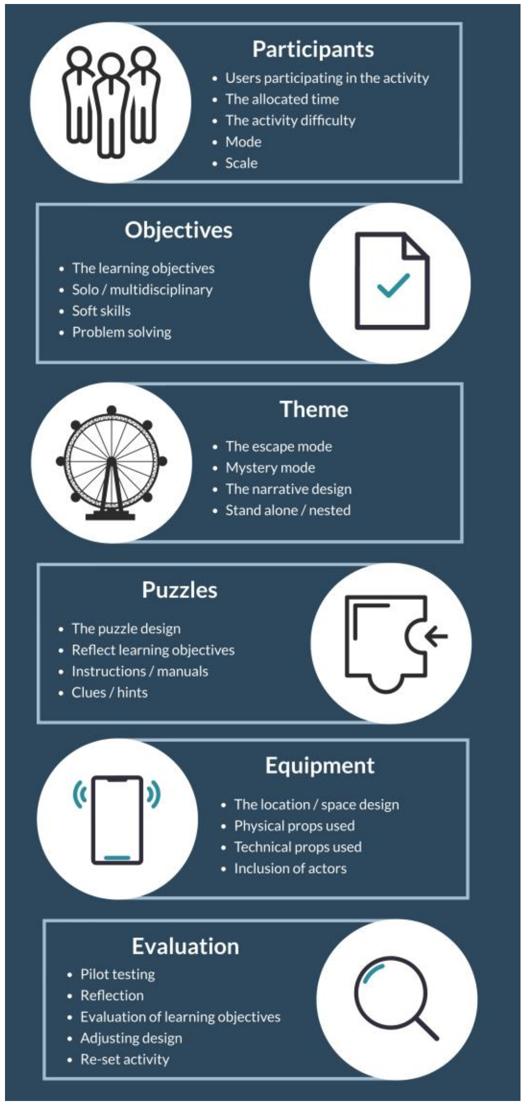


Figure 1. The escapED framework adapted from Clarke et al.[36]

The initial step of the framework was the consideration of the participant body who would be experiencing the escape activity. The activity was aimed at supporting chemistry students' understanding of the stereochemistry of metal complexes. Designed to last one hour, the experience was constructed to facilitate three students per instance of the activity. It was important to ensure that participants were challenged, but not to the extent where the activity was impossible to overcome. Therefore, puzzles with varying degrees of difficulty were designed which could be completed in parallel. This allowed students to temporarily step away from problems which may cause frustration without the worry of losing time or progress. As the escape room reached the latter stages, the output of these puzzles converged to a single answer that students required to access the final puzzles.

Secondly, learner-focused objectives were clarified to facilitate the creation of content. The revised version of Bloom's Taxonomy was leveraged to produce clear, measurable, and meaningful statements defining the learning objectives. The taxonomy provides a way to organize thinking skills into six conceptually different levels: remembering, understanding, applying, analyzing, evaluating, and creating.[37] The activity incorporated learning goals that were: (i) knowledge-related, requiring participants to recognize and identify presented molecular structures, (ii) analysis- and comprehension-related, requiring participants to inspect and determine different elements of metal complexes, and (iii) evaluation-related, requiring participants to describe and evaluate their progress.

The latter prompting higher-order thinking, making participants aware of their successes and mistakes.

Once the targeted principles of stereochemistry had been identified, the puzzles were prepared to address the learning objectives (Figures 2 and 3). The narrative allowed for the use of a specific style of instruction as well as the tone used in the clues and hints. Paper-based and electronic materials were provided to the participant groups. Paper-based clues incorporated the use of confidentially marked files requiring students to not only apply their knowledge of stereochemistry, but also decipher codes to further progress. This is a common component of escape rooms.[22] The electronic tools provided included the AR/iVR applications for the identification of the metal complexes. Evaluation of the game experience and learning objectives is embedded into the debriefing session.

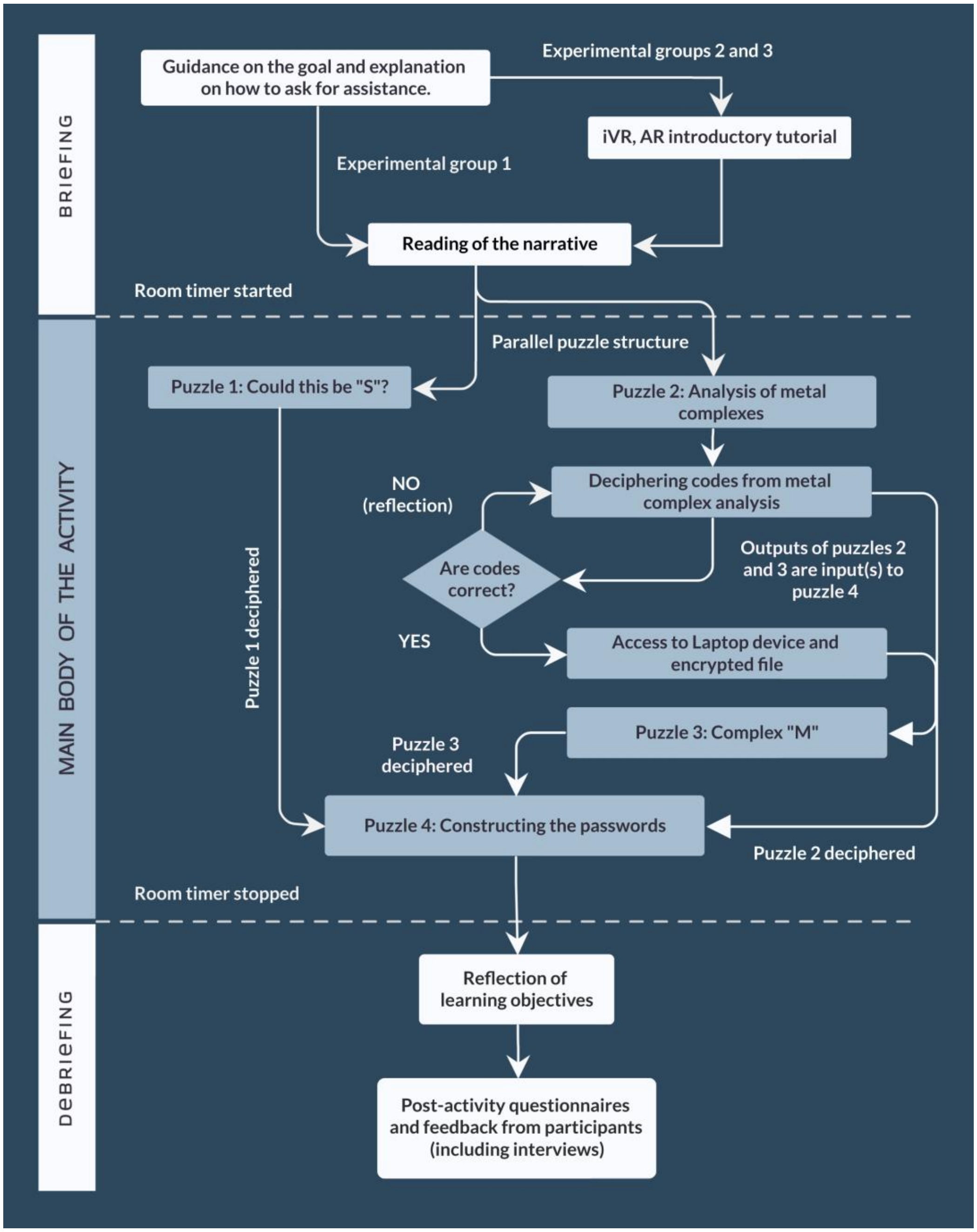


Figure 2. Sequence of the educational escape room activity employed for the research study. Participants are guided through an initial briefing leading to the main activity. On completion of the main activity, a debriefing session is conducted.

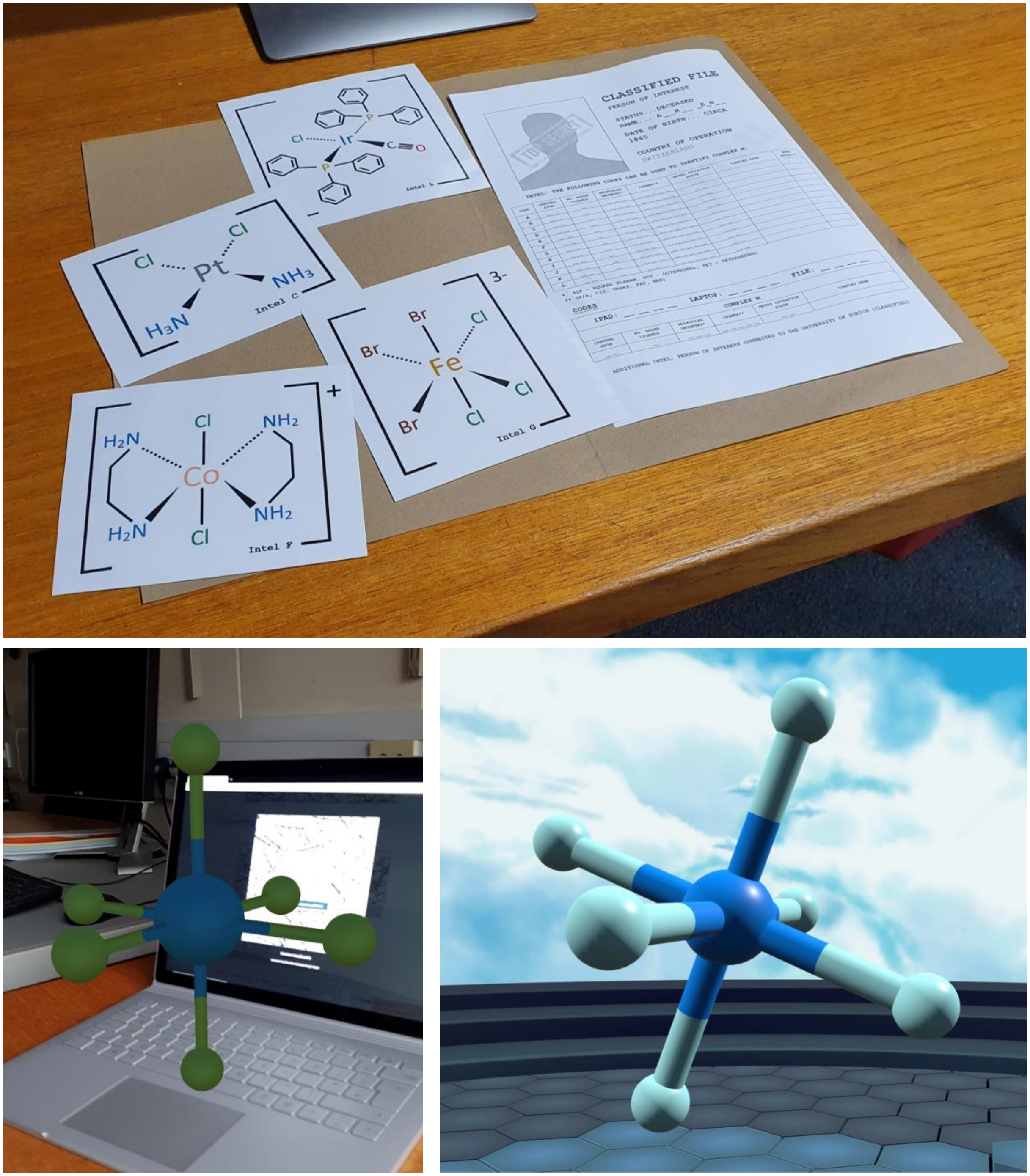


Figure 3. Examples of resources used within puzzle 2 (top). A representation of uranium hexafluoride in ChemFord rendered from an image marker located on the laptop display (bottom left), and Nanome (bottom right).

Overview of the Activity

Purpose of the Activity. This activity is designed to evaluate students' understanding of the principles of stereochemistry.

Goal of the Activity. Successfully solving the puzzle(s) within the allotted time of 60 min. The participants (3 students at a time) are given these instructions:

An enigmatic figure known only as “S” has surfaced with information of critical importance. Upon inspection, the information is inaccessible and attempts to brute-force entry have been unsuccessful. Accompanying the information is a series of clues which are believed to hold the key to constructing two passwords, unlocking the contents within. On opening the first of a series of puzzles, a countdown will commence, and if all are not solved within one hour, the information will be lost forever. Will you solve the puzzle in time?

Activity Learning Objectives. Achieving these objectives supports students’ understanding of stereochemistry principles:

- To be able to correctly distinguish between different stereoisomers of metal complexes
- To be able to correctly assign the oxidation state of metal atoms bound to various ligands within metal complexes
- To be able to decide whether a metal complex is tetrahedral, square planar or octahedral based on the three-dimensional projections and assign correct bond angles
- To correctly name metal complexes based on their molecular structure
- To develop soft skills such as communication and teamwork

Briefing before the Activity. The briefing is used as an opportunity to welcome participants to the activity and present details on how the experience will be structured. The narrative presented to participants directly links into the first puzzle. After this point, the facilitator is no longer directly involved in the experience and only provides hints when deemed necessary.

Puzzles within the Activity. The four puzzles of the stereochemistry escape room activity are synopsized in Table 2.

Table 2. Overview of the Stereochemistry Escape Room Activity

Puzzle	Type of Puzzle	Description of Puzzle	Successful Outcome of Puzzle
1: Could this be “S”?	Cipher	A simple cipher is used as an introductory puzzle to build student confidence, engage problem solving skills, and serve as an initial discussion topic.	Cipher is solved and participants understand how to undertake the remaining puzzles
2: Analysis of metal complexes	Molecular structure determination	12 intel image markers are placed throughout the room, each relating to a different metal complex. Participants must extract information pertaining to the central metal atom, bound ligands, isomerism, and molecular geometry. Depending on the participant group, physical molecular modelling kits, AR, or iVR is incorporated to assist with identification.	Correctly identifying the metal complexes allows construction of a series of passkeys required to log into a laptop and access password protected files containing the next puzzle
3: Complex “M”	Confirmation of answers	Students identify the answers from puzzle 2 to construct the passkeys. Access to the laptop device is only possible if the answers to the previous questions are correct. Upon accessing the secured file, a 13th complex (denoted complex “M”) becomes available.	Participants apply logic similar to that required in puzzle 2 to determine complex “M”
4: Constructing the passwords	Communication, cipher	Information obtained from completing puzzles 1–3 is needed to solve the final cipher. If information is missing or incorrect, final passwords cannot be constructed.	Construction of final passwords based on students being well-organized with their information and communicating well with one another

Debriefing after the Activity. On completion of the activity (or on the countdown hitting zero) the debriefing session is carried out. This session is treated as an important time of reflection on the learning objectives and to provide feedback on participant performance.

TOOLS

To assist participants with the completion of puzzle 2, three different tools were implemented into the activities. The first, which was provided to experimental group 1, was a set of physical molecular modelling kits. The molecular modelling kits allowed participants to construct and visualize molecules containing either an octahedral, tetrahedral, or square planar central atom. Experimental group 2 was provided with an AR application compiled onto iPad devices called ChemFord. ChemFord is a mobile marker-based application that allows an individual to view and manipulate (rotate, scale, and translate) single or multiple three-dimensional structures [simultaneously] of molecules, lattices and atomic orbitals.[38] Experimental group 3 was provided with a commercially available iVR software package called Nanome, developed by Nanome Inc.[39] To avoid user irritation and ensure that participants' working memory is dedicated to solving the problems presented in the escape activity, familiar visual affordances and signifiers were implemented to ensure the AR application is intuitive to users. Every distinct action users take within the application adds to their cognitive load.[40] Upon opening the application, trackable image targets are detected by the device camera and the corresponding molecular virtual object is augmented. No further actions are required by users. With respect to the intuitive design of the application, only essential elements that serve a critical purpose are visible on the user interface.[41] The interactive molecules used in puzzle 2 were imported into the iVR environment as Protein Databank files (.pdb), allowing them to be rendered within the software. The HTC Vive headset was utilized for this study and uses six degrees of freedom (incorporation of rotational and directional movement), tracked using the Lighthouse system.[42]

QUESTIONNAIRES AND INTERVIEWS

To explore students' perceptions, a questionnaire was constructed and distributed to participants following completion of the activity. The questionnaire was voluntary and available to each participant group for up to a week following the intervention. Eight different constructs were adapted from literature to examine the theoretical and practical underpinnings of the activity (Table 3). Constructs derived were chosen to investigate the students' perceptions to the AR/iVR tools implemented as well as the educational escape room activity. Students were required to rate their experience using a 5-point Likert scale (Figure 4). Semi-structured interviews were also employed. An interview schedule was produced containing questions based on the measurements shown in Table 3.[43–52] Two further question constructs were also introduced: (i) perceived usefulness;[43] and (ii) representational fidelity.[44] Prior works have shown both constructs to influence learning effectiveness when employing gamified teaching strategies.

Table 3. Questions Constituting the Post-Activity Survey

Measurement	Item	Question Sources
Control and active learning	This type of learning experience helps to get myself engaged in the learning activity	Adapted from Ai-Lim Lee, Wong, and Fung (2010)[a]
Cognitive benefits	This type of learning experience makes the comprehension of material easier	Adapted from Antonietti et al. (2000)[b]
Immediacy of control	The ability to change the view position of the 3-D objects allows me to learn better	Dalgarno et al. (2002)[c]
	The ability to manipulate the objects (pick up, change size) makes the learning experience more motivating and interesting	
Motivation	Learning using this tool was fun	McAuley et al. (1989)[d]
	After trying this type of learning tool for a while, I felt pretty competent	
	This type of learning experience did not hold my attention	
Perceived ease of use	Overall, I think that this type of learning tool is easy to use	Davis (1989)[e]

Perceived learning effectiveness	I learned a lot of factual information on this topic I was able to summarize and conclude what I learned I was interested and stimulated to learn more The learning activities were meaningful	Benbunan-Fich and Hiltz (2003);[f] Marks, Sibley, and Arbaugh (2005);[g] Martens, Bastianens and Kisrcher (2007)[h]
Reflective thinking	I was able to link new knowledge with my previous knowledge and experience	Maor and Fraser (2005)[i]
Satisfaction	I was satisfied with this type of computer-based learning experience I was satisfied with the teaching methods in this type of computer-based learning experience	Chou and Liu (2005)[j]

[a]See ref *45*. [b]See ref *46*. [c]See ref *44*. [d]See ref *47*. [e]See ref *43*. [f]See ref *48*. [g]See ref *48*. [h]See ref *50*. [i]See ref *51*. [j]See ref *52*.

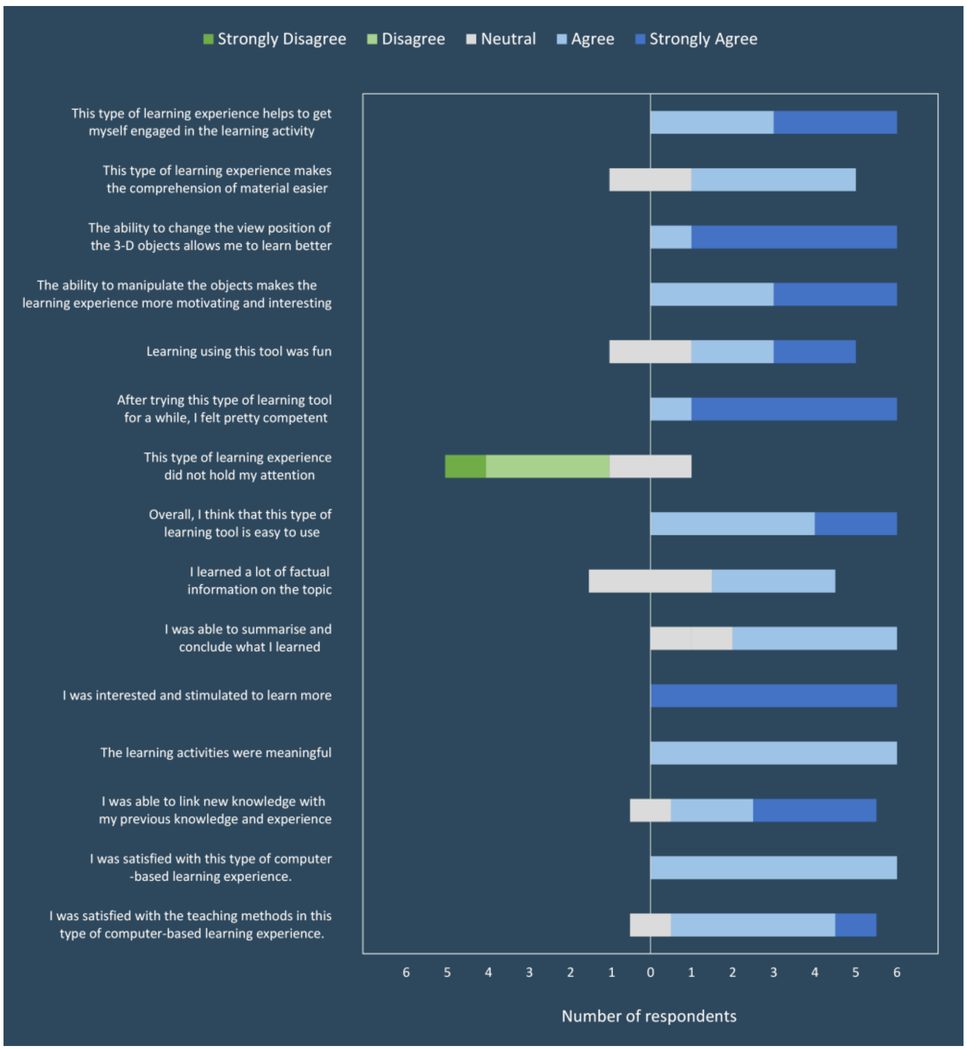


Figure 4. Student perceptions of the educational escape activity.

RESULTS

Three participant groups, consisting of three students each (n = 9) attempted the educational escape room. Of these, experimental group(s) 1 and 3 successfully “escaped” in 57 and 46 min, respectively, whereas experimental group 2 failed to complete the activity within the allotted time. Of the 9 participants in this study, 6 returned post-activity questionnaires and agreed to a follow-up interview (from experimental groups 2 and 3). Conducted interviews typically lasted around 30 min. Students had a very positive overall opinion on the educational escape room activity. All participants who responded stated that they either agreed or strongly agreed that the learning experience engaged them in the activity, and all strongly agreed that they were interested and stimulated to learn more.

Students agreed that the activities were meaningful in achieving the intended learning outcomes. The activity was designed with a focus on content interaction through engagement with multimedia. A key pedagogical affordance of AR and iVR is the ability to rescale virtual objects, allowing students a better understanding through manipulation of objects that would otherwise be imperceptible through interaction with the physical world. The construction of puzzle 2 placed both the AR and iVR technologies as core tools, with this key affordance central to its design.

Participants either agreed or strongly agreed that after experiencing the AR and iVR learning tools provided throughout the activity, they felt competent. In addition, participants either agreed or strongly agreed that the learning tools were easy to use. Interview respondents indicated that the tools were generally easy to use, stating that the ChemFord application compiled onto the iPad devices was "intuitive" with no observable learning frustration from students interacting with the AR technology. Participants agreed that they were satisfied with this type of computer-based learning experience.

It was further observed throughout the activities that participants utilizing the AR and iVR technologies engaged in deeper discussions regarding the properties of each metal complex with their peers. Discussions assisted participants as they used the technologies to dissect each 3D virtual complex and evaluated different structural properties such as the adopted geometry and exhibited isomerism. Throughout, evidence of intellectual quality was apparent as participants constructed and validated solutions to each problem based on substantive communication with their group members. Students believed that the immediacy of control positively impacted their learning. The ability to manipulate and change the view position of the 3-D objects positively affected the learning experience to make it more motivating and interesting.

Most participants agreed that the learning experience made the comprehension of material easier but also expressed neutral responses when asked if the activity provided the opportunity for individuals to learn a lot of information. Participant responses suggest the escape activity primarily functions as an opportunity to consolidate and test understanding. For acceptance, further work is required to evaluate how the escape room activity can be successfully implemented within the teaching and learning process, and how AR/iVR technologies can support this initiative.

Although not a primary research question in this study, the opportunity was taken to gather data regarding induced "simulation sickness" as studies increasingly outline reports of health concerns among users of head-mounted display systems.[34] All participants from experimental group 3 completed the health survey. No "severe" symptoms were reported and of those symptoms reported as "slight" or "moderate", post-activity symptoms had not increased in severity. (See the Supporting Information, Table S1.)

STUDENT PERCEPTIONS

Analysis of the participant interviews was completed through latent thematic analysis using the approach of Braun and Clarke,[53] by which all the information was transcribed line-by-line after interviews had been conducted to be subsequently grouped by themes. The initial broad themes were constructed based on frequency and similarity of responses which were then collapsed into core themes by eliminating redundancies and merging closely related major themes. Frequencies were used to highlight important areas for theme development. The process attempts to go beyond the semantic content of the data, and to start identifying the underlying ideas that are theorized as shaping the semantic content of the data. The data suggested a number of characteristics that appeared to influence students' perceptions on the effectiveness of: (i) the educational escape room activity as a learning environment and (ii) the AR and iVR technologies integrated.

Cognitive Benefits

Cognitive benefits related to the impact the AR and iVR interventions had on assisting students in appreciating the three-dimensional structures represented by the two-dimensional isometric markers provided. The capability of the AR tool to present the three-dimensional structure of each metal complex reduced student difficulty in dealing with abstract concepts such as isomer, ligand and bond angle identification through substituting for the need to visualize. This was apparent throughout the activity, where students using the AR and iVR tools exhibited greater confidence and competency when discussing the problems with their respective team members.

> "…I do struggle to visualize things but if I do go through questions, with time, I can usually get the answer. However, with this, I can visualize them better…" (Interviewee 5)

> "Honestly, it was easier, and I liked how interactive it was. I feel like I am more likely to get the wrong structure when using the molecular models… …Being able to move it and see the isomer itself is useful…" (Interviewee 2)

Overall, students expressed more positive views towards the interventions provided in the AR and iVR experimental groups in comparison to the group utilizing traditional molecular modelling kits. It was interesting to note that participants also commented that the AR tools would be a welcomed addition into the classroom. The AR application not only aroused interest and curiosity, but also encouraged active learning through interaction. Due to its adaptability, not only can it be easily upscaled, but also made available for use outside the classroom.

Perceived Learning Effectiveness

A minority of our participants expressed low levels of interest in the topic of stereochemistry prior to partaking in the educational escape room activity but articulated that they understood the importance of the topic. Some participants felt that they possessed low visualization skills, which was a central source of frustration.

> "Personally, not that interested, I can see how it's useful—I'm not very good at visualizing…" (Interviewee 6)

However, those who reported lower levels of interest in the subject topic commented that they experienced greater levels of engagement and interest. This resulted in a perceived benefit to learning. One of the main purposes of the educational escape room activity is to motivate students, to involve learners who are more reserved in the learning environment. Participants also perceived a disadvantage to the educational escape room regarding the initial structure of the activity. It was acknowledged that after the initial briefing, students were left to investigate and analyze the first puzzle. Many stated that the uncertainty of how to progress through the initial stage of the activity induced nervousness. However, to the observer, this was no longer apparent after groups progressed into the first puzzle phase. For the three experimental groups that participated in the activity, this occurred within the first 5-10 min. A majority of participants also stated that they found the activity as a better method to consolidate prior knowledge.

Perceived Usefulness

Though participant responses suggested a clear link between initial student nervousness and the direction and structure of the educational escape activity, the experience was viewed as challenging and fun.

> "I thought it was fun, at first, I was nervous, because I didn't know what I was doing in the beginning…" (Interviewee 2)

All participants expressed that they would like to see both the AR and iVR tools, plus escape activities, implemented throughout further areas of the chemistry syllabus. Most students also commented that the methods employed may help engage others when trying to discuss chemistry outside of the formal classroom. Naturally, seldom can students incorporate the discussion of concepts like stereochemistry into spontaneous conversation with others outside of formal education.

> "If I wanted to get someone to be more interested in chemistry, like my family; as in trying to talk about chemistry, and I did this activity, they might be more interested…" (Interviewee 1)

Representational Fidelity

Many participants expressed preference when using the AR tool as they perceived clear-cut advantages when compared to the alternate methods. Speed, convenience of generating the molecular structures (through scanning the isometric markers; see Figure 5), ability to scale, move, and rotate three-dimensional objects were major incentives for using AR technology.

> “I think it makes it quicker for me to visualize it, with just a picture, it takes me a few minutes to be able to visualize it. It’s quicker in my mind…” (Interviewee 3)

Figure 5. Physical model of methane (left); methane as virtually represented in ChemFord (right).

Participants considered these advantages paramount in their own ability to arrive at the correct answer quicker than if using physical modelling kits. No preference was reported in terms of visualization between the AR or iVR technologies.

> “I think I would prefer to use the iPads over physical models… …It takes less time… …Being able to rotate them was great…” (Interviewee 2)

Satisfaction

Participant responses reveal that gamified actions such as the educational escape room enhance engagement and improve motivation, group work, communication, and commitment to the learning tasks within the activity. The introduction of the element of time pressure was seen to enhance motivation and competitiveness.

> “Yes, I thought it was good, and that I worked better under the stress. I also felt more active because I was moving around when doing the work…” (Interviewee 1)

Students expressed that the active nature of the learning environment also encouraged collaboration, which was apparent through observation. The teams worked well when there was a common context for communication.

> “It’s quite cool. It is more of a group activity than just doing questions. It’s easier to work together than just having a piece of paper…” (Interviewee 5)

To conclude the interviews, participants were asked the worst aspects of the activity. All participants answered that they did not think there was anything they disliked, and all would recommend the activity to others.

DISCUSSION

Research Findings

There is a need to create innovative teaching strategies that can be merged with immersive technologies.[54] The development of educational escape activities embedding elements of AR/iVR can merge the educational qualities of games, the teamwork and problem-solving skills associated with commercial escape rooms, and attractive technologies to generate effective activities appealing to students. Active learning, and particularly gamification, were employed to create, implement, and evaluate an educational escape room experience incorporating a serious gaming strategy. The activity adequately covers the content seen in the classroom and can be used as a complementary tool that helps students reinforce their understanding of stereochemistry.

Students' perceptions to the developed activity were captured through qualitative assessment. Interview responses were very positive and the initiative was very successful at capturing students' interest, as evidenced with participants strongly agreeing that they were interested and stimulated to learn more. These findings are in line with previous studies where educators have incorporated games into the teaching process to aid students with reviewing and reinforcing stereochemistry topics.[33] Similarly, from survey feedback and informal observation, participants were shown to be highly engaged and active throughout the activity. Extrinsic motivational factors such as time constraints and competition were mentioned by interview respondents.

Participants expressed initial nervousness when participating due to the absence of a clear path of progression, a property which is commonplace with commercial escape rooms. Not only does this result in potentially significant amounts of time lost initially but may also lead of demotivation and frustration in students. However, as the activity progressed from the briefing to the first puzzle phase, it was observed that students became more confident and comfortable with the activity once they had established an understanding of what was required to progress—whether this was the discovery of an important piece of information, or resource. To aid the transition from the briefing phase to the initial puzzle phase, the briefing session should address, at minimum: (i) the narrative, if incorporated into the activity; (ii) guidance on the goal and how to ask for assistance when required; and (iii) an indication of which mechanic of the room students should focus attention their attention, once the activity begins. Design choices should create affordances that subtly inform students of the next action they should take. Another suggestion is to make the first puzzle very easy to further facilitate participants getting started with the activity.

Students reported a perceived benefit of interacting with 3D virtual representations and strongly agreed that the AR/iVR technologies helped them overcome abstract concepts. However, due to the lack of quantitative data within this study, it was not possible to establish sound statistical evidence of improved performance. The educational escape activity grants participants complete freedom within their environment and the social nature of the game allows students to learn in a cooperative environment. How the observed group dynamic within the environment effected the outcome performance was noteworthy. Experimental group 3, the best-performing group in terms of time, were very vocal among team members with their discoveries and progress. The escape activity stimulated students to discover as a team providing the opportunity to develop adaptive and responsive skills expected of each participant. Experimental group 2 failed to complete the activity within the allotted time, not due to misunderstanding the conceptual nature of the chemistry topics covered (where they scored very highly), but due to an inability to overcome the mechanics of the game elements in play. This highlights a need to ensure the integration of meaningful game mechanics relevant to pedagogical objectives and an avoidance of the superficial.[55]

Practical Implications

The process of developing the resources required to carry out the activity raised points of discussion. Generating educational escape activities can require potentially expensive resources and any permanent physical installation is likely to be unsustainable. Therefore, escape room activities should be portable and sustainable. The low financial cost of developing the educational escape room activity used in this study is a hugely positive aspect when compared to other GBL activities. Construction of the paper-based resources utilized materials that are commonly available in practical classrooms. Lamination of paper-based resources to extend their reusability was the highest direct financial cost. ChemFord was constructed entirely (by one of us, DE) using free available software and can be downloaded directly onto students' personal devices.[56] iVR tools such as Nanome are also available at no additional cost. However, it is recognized that not all educational institutions will have iVR hardware readily available.

Further refinement will be facilitated by the capability to involve large cohorts of students simultaneously. This will likely be critical for incorporation into mainstream teaching. Most reported studies are composed of participant groups of 3–7 students per session.[57] However, for larger groups of students, which is common in a university setting, facilitators must expend considerable effort and time over multiple sessions. The incorporation of augmented technologies and online collaborative spaces is a potential solution to this challenge.

The activity is easily portable, and the entire contents could be easily carried in one box by a single facilitator. For this study, multiple classroom locations were employed to ensure feasibility that different locations could house the activity. Although participant groups in this instance were small (with only 1 facilitator present) it would need to be seen whether further facilitators would be required upon scaling of the activity. In this instance, the event was manageable. Although the briefing and core activity could be completed in the 1 h class session, additional time was required to complete the debriefing session. To compensate for the extra time required, future iterations of the escape activity will modify the puzzle mechanics to ensure that the briefing, core activity, and debriefing segments can all be completed within 1 h.

During construction of the puzzles, it is important for educational escape room designers to understand how the difficulty of each puzzle should be set to reflect both the puzzle mechanic and the subject material. A puzzle that is too difficult will result in frustration, anxiety, and demotivation and may even result in students being unable to complete the activity, whereas puzzles that are too easy will not provide students with sufficient satisfaction. Prior works have outlined the percentage of students who successfully completed the researchers escape room intervention but fail to provide information about those students who were unable to complete the activity. Such data is essential to enable the evaluation of escape room activities to enable improvements in subsequent editions.

Pilot testing was essential in the iterative construction of the activity and revealed the requirement of hints to provide guidance to participants. The management of hints is important for the success of commercial escape rooms, but prior works have not presented significant research into the incorporation of hint management systems. Common methods include providing hints on demand when asked by the players or provided when considered necessary by the facilitator. Previous studies have implemented hints into an educational escape activity that required students to pass a small quiz to earn the right to get help from the instructors.[58] In an educational setting, hints steer participants to complete the activity within the allotted time. Although not a primary research goal of this study, further work into the development of innovative hint management systems for educational settings are required.

STUDY LIMITATIONS AND FURTHER WORK

This study has its limitations. The most pressing is the small study sample utilized, thereof the small amount of observational data. Due to the window to operate the activity, the number of participants was limited. Furthermore, the feasibility assessment of the activity was carried out by a single individual. To further evaluate the learning potential of the educational escape activity employed for this study, repeat activities with a larger cohort of participants are required. No quantitative analysis was undertaken for this study due to challenges regarding the small research sample size, but will be included in future work to allow research into factors such as potential learning gains. Examples of extrinsic motivational factors were mentioned by interview respondents. Further work examining the effects of intrinsic and extrinsic motivation on students' perception and performance in educational escape initiatives would be a welcome addition.

For successful implementation of educational escape room activities, three considerations that require addressing are:

1. How the educational escape room activity fits within the holistic teaching and learning process and its requirements
2. How to evaluate individual participants to ensure knowledge and skill competency has been achieved
3. How an educational escape room incorporating AR/iVR tools can be upscaled to accommodate larger groups of concurrent players

Research regarding this area is scarce, with limited studies addressing this topic.[59] One alternative approach used to accommodate larger participant groups is the use of escape "boxes" such as Breakout EDU.[60]

Despite the growing interest in educational games for learning, further empirical evidence is necessary to evaluate the potential of GBL with regards to both the learner and game design. According to student feedback and observations, the escape room experience was an engaging activity. However, research regarding how key elements of the activity, such as the briefing and debriefing sessions, should be designed and constructed is yet to yield definitive insight. The debriefing session is important as a time of reflection on the learning objectives and to provide feedback.

With the implementation of AR/iVR software into the activity, it is critical to differentiate between software errors and puzzle elements introduced as part of the activity, as this can cause confusion within the whole experience. The potentially significant technical expertise required by designers to develop, include and maintain interactive computer-based systems is currently considered a major drawback. For successful implementation, educational facilitators will require the skills to recognize and troubleshoot problems whilst developers will need to carefully test applications as well as to think thoroughly how to prepare them so as to be of high educational value for students.

Finally, future work should concentrate on defining the game mechanics most appropriate to addressing both the pedagogical and learning objectives. Given that there is limited work on serious gamification through the utilization of escape rooms in chemistry education, and even less incorporating AR/iVR tools, there is a potential to gain considerable information about the development of key chemistry competencies using this teaching strategy.

CONCLUSION

This research study reports the implementation of an educational escape room conducted for higher education chemistry students. Initial results indicate the effectiveness of using educational escape rooms on student engagement. This study attempts a novel approach to comparing educational escape room activities implementing technologies such as AR and IVR. It was found that students valued tools such as Augmented and Immersive Virtual Reality when learning stereochemistry concepts. According to the data provided in this work, educational escape rooms promise to be a valuable contribution to chemistry teaching and merit further research in the educational community.

The design approach[36] provided many positive results. Yet, further work is required in the design and facilitation of educational escape room activities implementing technical elements, which can be successfully upscaled for larger groups of concurrent players and how best to facilitate the progress of participating students.

Further questions that have been raised by this study in need of investigation include how educational escape room activities can be implemented into the holistic teaching and learning process and to evaluate individuals participating in these activities for competencies and skills related to the learning objectives.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.0c01283.

Questions utilized, and results, on the topic of “Simulation Sickness” (DOCX)

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