Supporting student active engagement in chemistry learning with computer simulations: Five actions (5As)

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Abstract

Science, technology, engineering, and mathematics (STEM) are widely recognised as paving the way towards national sustainable development and innovative socioeconomic transformation. However, some students consider STEM as a difficult field to study. Consequently, teachers need to shift from traditional teaching approaches towards participatory and interactive methods to promote the development of students' higher-order thinking, critical reasoning, and problem-solving skills. This study is an attempt to investigate how computer simulations can contribute to engaging students' active participation in new knowledge creation in chemical bonding problem solving with computer simulations. Empirical data were collected through interviews, a survey and a test on secondary school student performance in Rwanda. The findings reveal four main forms of participating in knowledge construction with computer simulations: self-reliance, peer collaboration-reliance, teacher-guided-reliance and strategic variation-reliance. The study found no statistically difference between male and female students' preferences to engage in these forms and in their performance in terms of higher-order thinking skills in chemical bonding problem solving with computer simulations. Moreover, the findings demonstrate that computer simulations can help students to create multisensory connections with the object of learning enabling them to become actively engaged in chemistry learning through various settings. Consequently, the lines between abstract concepts and related chemical reactions and processes become closely related in a virtual reality. Finally, this study suggests five actions that teachers can undertake to support student active engagement in chemistry learning with computer simulations.

Keywords: chemistry education, higher-order thinking, ICT, knowledge construction, multisensory connection, Rwanda, STEM

Introduction

In most sub-Saharan African countries, access to education has continuously increased since the implementation of the Education for All global movement in 1990 (Vavrus, Thomas, & Bartlett, 2011). Science, technology, engineering and mathematics (STEM) are increasingly and globally considered as the key drivers to national socioeconomic development and welfare (Freedman, Marginson, & Tyler, 2019). The Government of Rwanda identified STEM among the strategic priorities of its *Education Sector Strategic Plan 2018/19 – 2023/24* (Ministry of Education, 2018). The use of technology in education has become an issue of critical importance to students, teachers, institutions and governments during the current COVID-19 pandemic, when technology has widely become the primary means to convey learning (UNESCO, 2020). In line with Sustainable Development Goal 4, the World Bank-funded African Centre of Excellence for Innovative Teaching and Learning Mathematics and Science (ACEITLMS) was established at the University of Rwanda in 2016, as a response to the longstanding challenge of quality and equality of education in STEM on the continent. One of the missions of this centre is to leverage the use of technology in building human capital at all educational levels.

Nevertheless, broad criticisms continue to rise pinpointing that, in the context of Rwanda, "*teaching methods remain largely teacher-centred*", with little open debate and teaching of critical thinking skills (Hilker, 2011, p. 2). For example, according to the study conducted by Byusa, Kampire, and Mwesigye

(2020), secondary school chemistry teachers experience challenges to provide support to their students working collaborative in small task-based groups. Globally, the fact is that some students complain that chemistry is a difficult subject to study when teachers rely on traditional teaching methods (Nahum et al., 2010; Musengimana, Kampire, & Ntawiha, 2021).

On the other hand, studies have shown that among the factors contributing to infuencing students' positive attitudes towards learning chemistry include interactive computer simulations (Rutten et al. 2012; Gambari et al. 2016). Though several reforms have been undertaken to leverage the use of technology to expand access to education, reinforce teacher professional development and enhance student performance in schools especially in the context of Rwanda (Mukama, 2009, 2010), issues about how students engage with computer simulations for chemistry learning has remained almost silent; hence, the focus of this study.

Theoretical framework

Computer simulation in support of student active learning

Gunter, Demir, and Giner (2011) report that computer simulations can assist students to grasp complex mathematical operations and to understand some theoretical issues in chemistry. They also argue that these tools can help students engage actively in critical thinking and reflection is solving chemistry problems. According to Landriscina (2013), simulations can play different roles depending on specific contexts. Landriscina (2013, p. 4) identifies the following simulations' functions:

- *understanding*, to gain knowledge of theories, models, and structures;
- *prediction*, to obtain a currently reliable imagine of a future occurrence;
- *decision support*, to support individual or team decision-making skills;
- *design and modeling*, to explore various design options, verify the quality of a product's performance before production, and to refine production processes;
- *training*, to teach operational and technical skills and work methods;
- *entertainment*, for curiosity, fun, and competition.

Computer simulations seem to fill the gap between active and traditional learning methods. In fact, several studies reveal that computer simulations are more effective than traditional methods of teaching and learning (Akcay, Feyzioglu, & Tuysuz, 2003; Koomson, Safo-Adu, & Antwi, 2020). These studies also report that students learning with computer simulations tend to express positive attitude towards chemistry. Koomson, Safo-Adu, and Antwi (2020) add that students who acquire collaboratively with computer simulations and computerised molecular modeling software perform better than those working in solo. Gambari, Gbodi, Olakanmi, and Abalaka (2016) also state that computer simulations outstand ordinary computer tutorial instructional package in terms of increasing students' performance. Further, Gambari et. al. (2016) argue that computer simulations contribute to rise student intrinsic and extrinsic motivation in chemistry learning. Accordingly, Gambari et. al. point out that students like to deal with different exercises on balancing chemistry equations with computer simulations on their own without waiting the teacher's guidance. However, several studies confirm that good performance in chemistry while using computer simulations does not depend on gender (Adesoji & Babatunde, 2005; Fagbemi, Gambari, Oyedum, & Gbodi, 2011; Gambari et. al., 2016; Uzezi, & Deya, 2020). On the other hand, Nahum, Mamlok-Naaman, Hofstein and Taber (2010) report that some teachers and students misunderstand the concept of chemical bonding and consider it very difficul to grasp through the conventional method of teaching and learning due to its abstractness.

Williamson (2015) emphasizes that computer simulations convey images and motions which enhance students' problem-solving abilities and understanding in chemistry. Gambari et. al. (2016) maintain that computer simulations contribute to making learning a fun. The same authors also report that the features of computer simulations include a sound, visual images, and moving pictures and a text on the screen. Gambari et. al. conclude that these features translate chemistry concepts' abstractness into something seemingly concrete through a virual reality.

Sahin (2006) affirms that computer simulations can be used as a pedagogical tool to simulate labs and, therefore, cut the costs spent on expensive reagents, reduce chemistry hazardous waste and conduct experiements that would be impractical in normal physical labs. Sahin contends that computer simulations can allow students to conduct open-ended experiences that can trigger inquiry-based learning. Sahin (2006) and Rutten, van Joolingen, and van der Veen (2012) are in accordance to say that student engagement with computer simulations depends to a large extent on how teachers support their students and on learning conditions they set up. Thus, Rutten et al. (2012) suggest that the place of computer simulations within the curriculum needs to be evaluated and valued.

Computer simulation as a mediating tool to construct knowledge

Mukama (2009) explains that knowledge construction in computer-supported social practice is a continuous process that requires linking students' active participation in a dynamic learning environment. In this regard, Mukama (2009) identifies three types of student engagement: *Passive ICT users*: this is a category of students who always have excuses and keep complaining that ICT is hard to use or that they are overwhelmed by other responsibilities. *Passive ICT users* usually prefer to use traditional teaching/learning methods. *Reluctant ICT users*: are those who acquire new technologies successfully sometimes with passion but who do not use them to make a difference in their teaching or learning practice. Mukama (2009) explains that *reluctant ICT users* can use technology effectively but rarely and always seek for refresher courses. *Active ICT users*: these are change agents and volunteer to provide support to their colleagues who may experience challenges with technology. According to Mukama (2009) active ICT users keep updating their knowledge and skills to be at the top. In a different paper, Mukama (2010) reveal that students adopt one of the three learning patterns in a computer-supported collaborative task-based activity, namely, *individual-led, group-led and a mixed pattern*. Mukama (2010) contends that students working in a computer-supported group-led pattern are more effective in terms of new knowledge construction than other learning patterns. In computer-supported social practice, the group-led pattern is characterised by *Initiation (I)* of a task by the teacher/computer, *Discussion (D)* of the task among group members before any response attempts, group *Response (R)*, and then *Follow-up (F)* by the teacher/computer; hence, the name *IDRF pattern*. Wegerif, Littleton, and Jones (2003) pinpoint that the IDRF pattern demonstrates a distinctive way to increase students' understanding in computer-supported collaborative learning.

Constructivism underpinned by Wegerif et al. (2003) and Mukama's (2009, 2010) studies on computer-supported collaborative learning is also reflected in some studies on computer simulations (Pantelidis, 2009; Rutten et al., 2012). The point is that computer simulations can allow students to interact and manipulate objects presented in virtual worlds. Pantelidis (1995) asserts that computer simulations encourage students active engagement and present an environment conducive for collaborative learning. In some instances, Pantelidis (1995) suggests that computer simulations transcend cultural and language barriers.

Drawing from this literature review, it is clear that previous studies have focused much more on exploring the benefits and challenges of using computer simulations in different contexts of STEM education. Several authors analyzed extensively the effects of computer simulations on student performance and attitudes in STEM in comparison with traditional teaching and learning methods. Some studies mention without a deep analysis that computer simulations provide an environment conducive to foster student collaboration. However, little is known about how students engage in knowledge construction with computer simulations in STEM classes especially in chemical bonding problem solving. The present study is therefore an attempt to address this gap. The following research questions will guide this study:

1) What are the contextual drivers in chemical bonding problem solving with computer simulations?
2) How do students strategize knowledge building in chemical bonding problem solving with computer simulations?
3) What are the outcomes of learning to solve chemical bonding problems with computer simulations?

Method

Data were collected in 2020 in a boarding secondary school purposely selected from the Western Province in Rwanda. This school had two science combinations with the chemistry as a major subject and a computer lab connected to the Internet. The class randomly selected to take part in this study was composed of 40 students (17 boys and 23 girls). These students followed a session aiming to explain the purpose of the study and to invite them to collaborate. They all agreed to participate voluntarily and signed individual consent forms. A chemistry teacher of this class received a training organized by the research team on how to integrate and use computer simulations in teaching and learning chemical bonding problem solving. Most simulations used were borrowed from the Khan Academy and YouTube channels. After the training, this teacher taught her students the same content using the same digital tools. Students had access to the computer lab to ensure that they could use simulations at their convenience. These simulations included an audio explaining chemical reactions and processes.

Right after the completion of the chemical bonding unit, 6 students (3 boys and 3 girls) were randomly selected to be interviewed on their experience to study chemical bonding problem solving with computer simulations. To ensure the participants' anonymity, they were given pseudonyms. Though interviews were conducted in Kinyarwanda, the discussions were peppered with chemistry terms in English. The interviews were audio-recorded, transcribed verbatim and then translated in English. Each interview lasted approximately 20 minutes.

The data from interviews were analysed qualitatively. The participants' utterances were recorded in a matrix indicating questions of interview guide. Each paragraph was coded and concepts representing central analytical ideas were written in margins. Afterwards, these concepts were closely scrutinized in terms of their similarities and differences, allowing the grouping of those with similar objects under common themes. These themes were gradually polished and, later, they became the headings of the section on findings. Other concepts under each theme were further developed into explanatory descriptors. Memos and diagrams were also used to track comparison of patterns and potential relationships between emerging concepts.

The preliminary interviews' analysis revealed four different forms of participating in knowledge construction with computer simulations, namely: *self-reliance*; *peer collaboration-*

reliance; *teacher-guided reliance* and *strategic variation reliance*. Thus, a follow-up survey was conducted with 37 students (17 male and 20 female students who were then present in class) to confirm whether these forms of participating in knowledge construction with computer simulations were consistent. The students were asked through a nominal scale questionnaire to identify their preferences in terms of the ways they would like to participate in learning chemical bonding problem solving with computer simulations. Data from the questionnaire were recorded and gender-desegregated in a spreadsheet (See Table 1). Therefore, a chi-square (χ^2) was performed in order *to analyze whether there is a difference between female and male students' preferences in terms of the forms of participating in knowledge construction with computer simulations*.

On the other hand, the theme *"higher-order learning skills"* emerged from interviews. To understand *whether there was a significant difference between boys' and girls' performance in terms of higher-order thinking skills with computer simulations*, an independent sample *t*-Test was performed after checking all required assumptions. This time, 35 students (14 boys and 21 girls) were present in class and voluntarily agreed to sit for the test administered after the intervention. To ensure its reliability, the instrument measuring student performance was first piloted with students who had completed the chemical bonding unit through a traditional method of chalk and talk and it was revised accordingly. The pilot revealed the coefficient Cronbach's alpha equivalent to 0.79, which is greater than the standard value of 0.70. Therefore, the calculated Cronbach's alpha indicated a satisfactory internal reliability, which suggests that test items were consistently measuring student performance. Data from the instrument were analyzed using SPSS 16.0.

Findings

Forms of participating in knowledge construction with computer simulations

The findings demonstrated that students adopted different ways to solve chemical bonding problems with computer simulations. Students' arguments during the interviews revealed four different forms of participating in knowledge construction with computer simulations, namely: *self-reliance*; *peer collaboration-reliance*; *teacher-guided reliance* and *strategic variation reliance*. *Is there a difference between male and female students' preferences in terms of the forms of participating in knowledge construction with computer simulations?* The students were asked to identify their preferences in terms of the ways they would like to participate in learning chemical bonding problem solving with computer simulations. The results of the survey are summarized in Table 1.

Table 1: Forms of participating in knowledge construction with computer simulations

Observed Frequencies	Self-reliance	Peer collaboration reliance	Teacher-guided reliance	Strategic variation reliance (exploring computer simulations…)				**TOTAL**
				…sometimes individually and sometimes with peers	…sometimes individually and sometimes with a teacher	…sometimes with peers and sometimes with a teacher	…sometimes individually, sometimes with peers, sometimes with a teacher	
Male students	1	4	4	1	2	2	3	**17**
Female students	1	4	6	0	0	2	7	**20**

TOTAL	**2**	**8**	**10**	**1**	**2**	**4**	**10**	**37**
Total percentage	**5%**	**22%**	**27%**	**3%**	**5%**	**11%**	**27%**	**100%**

The general picture of this table shows that the majority of chemistry students in the context of Rwanda prefer to seek for teacher-guidance in order to solve chemical bonding problems with computer simulations. These figures show that 70% of students seek guidance from the teacher in one way or another (11 boys and 15 girls). These students include *teacher-guided students* representing 27% and *strategic variation-reliant students* (43%), i.e. those who explore computer simulations either sometimes individually and sometimes with a teacher (5%); or sometimes with peers and sometimes with a teacher (11%); or again sometimes individually, sometimes with peers and sometimes with a teacher (27%).

The study demonstrates that the forms of participating in knowledge construction with computer simulations do not depend on whether students are boys or girls. In fact, with df = 6, it was noted that $\chi_0^2(4.79) < \chi^2(12.59)$. In other words, gender and preferences to participate in different forms of participating in knowledge construction with computer simulations are independent.

The narrations of the six students interviewed have been used to substantiate the meaning embedded in students' preferences:

1) *Self-reliance*: this form includes students who consider computer simulations as interactive, interesting, motivating, and a well-organized material in a way they can learn with it individually (5%). Tereza put it in this way: "When I was exploring computer simulations individually, I was extremely curious to watch the next step. I was open mind". It seems that this curiosity to explore further the learning material played a role to keep some students in isolation together with their computers.
2) *Peer collaboration-reliance*: 22% of chemistry students belonged to this form. During the interviews, the students reported that collaboration between peers helped them to push their understanding to a higher-order thinking level beyond what they could achieve alone without support. For example, Mariya argued that collaboration with peers opened for her an opportunity to discuss with them challenges she was facing, unpack them and solve them.
3) *Teacher-guided-reliance*: as referred to above, 27% of students preferred to seek support from their teacher only. Trying to explain the reasons behind this dependence, some students claimed that the teacher helped them to understand most difficult issues regarding chemical bonding problem solving.
4) *Strategic variation-reliance*: this form of participating in knowledge construction with computer simulations represents 46% of chemistry students, i.e., 17 students (8 boys and 9 girls). This form denotes some variations in strategizing knowledge construction while exploring computer simulations:
   a) *Exploring computer simulations sometimes individually and sometimes with peers*: this component indicates that individual students do not disappear in a group of peers; they worked individually and asked for peer support when it was really required.
   b) *Exploring computer simulations sometimes individually and sometimes with a teacher*: from the interviews, it can be noticed that the students considered their teacher as someone more knowledgeable than anyone else. They used to come to her and asked for clarification for any difficult questions they came across while working individually.
   c) *Exploring computer simulations sometimes with peers and sometimes with a teacher*: 11% of chemistry students, i.e., four students (2 boys and 2 girls) belong to this form of

participating in knowledge construction with computer simulations. In their narrations during the interviews, these students voiced at length their active involvement in a collective work either with peers or with the teacher.

d) *Exploring computer simulations sometimes individually, sometimes with peers, sometimes with a teacher*: this form of participating in knowledge construction with computer simulations is one of the most preferred by students (27%). Drawing from the interviews, the students explained that the more interaction, the higher their understanding.

This section has indicated that chemistry students tend to adopt different forms of participating in knowledge construction with computer simulations in search of deeper understanding of the learning material. Most chemistry students strategically varied the forms of participating in knowledge construction. Thus, the strategic variation-reliance suggests that learning conditions with computer simulations need to be reorganized in a way students, boys and girls, are given a chance to actively participate in learning activities that can allow them to collaborate with the peers and/or the teacher.

Creating multisensory connections between students and the object of learning

The findings revealed that most students who participated in the study affirmed that they were excited to learn chemical bonding problem solving with computer simulations. They explained that this enjoyment reflected not only the computer simulations' power to convey the object of learning but also the visible, audio, readable, motion and interactive connections that these tools create.

Students learning chemical bonding problem solving with computer simulations were attracted by *visible connections* pertaining to these pedagogical tools. For example, Petero explained: "I had some confusion about the molecular shape and geometry. […] After watching with my own eyes how things happen, I got a clear understanding because when you see with your own eyes you understand better." This excerpt denotes how computer simulations played the role to bring the learning material to the students' proximity.

In addition to appreciate visible linkages emerging from computer simulations, Tomasi, pinpointed the *motion connection* as follows: "I liked to see in a concrete way how electrons move around the nucleus and how they jump from one energy level to another and how atoms acquire stability after the formation of a covalent bond". Two more connections emerging from learning chemical bonding problem solving with computer simulations were *audio* and *readable*. The following excerpt from an interview with Mariya is illustrative: "With simulations, you see with your eyes how things happen, you hear explanations behind what you see, and you read what is written."

Lastly, students' engagement with the learning material denotes *interactive connection* created by computer simulations involving hands-on skills to solve minds-on challenges in a progressive manner as Tereza argued: "In class, we were concentrated on the teacher but with simulations we are concentrated on the lesson." Monika concluded: "I was extremely motivated to follow each and everything." Thus, learning to solve chemical bonding problems with computer simulations helped students to create multisensory connections with the object of learning.

Shift from first- to higher-order thinking skills

The findings reveal that the outcomes of learning chemical bonding problems solving with computer simulations can be categorized in two levels of cognitive processes: *first- and higher-*

order thinking skills. *The first-order thinking skills* reflected the outcomes of learning created by simple encounter of computer simulations. *The first-order thinks skills* conveyed by computer simulations included memorization, enjoyment, motivation and commitment to study chemistry. The findings indicate that these skills were developed mainly just through the students' encounter with computer simulations.

On the other hand, the findings demonstrate that computer simulations can help students to acquire *higher-order thinking skills* including analyzing, evaluating, creating, elaborating, changing, comparing, contrasting, critical thinking, problem solving, and explaining. For example, Petero pointed out: "I wished to keep searching and exploring other computer simulations related to the subject". In fact, the need to conduct research on the Internet and explore other computer simulations beyond indicative content proposed by the teacher was echoed in most students' utterances. Personal and societal fulfilment was another aspect highlighted by students during the interviews. Andereyasi expressed how his experience with computer simulations inspired him and his classmates to create a science club: "After learning with computer simulations, we had an idea to start a science club where we can explore further and in-depth various simulations in science. I have seen that girls supported the idea faster than boys." Thus, chemical bonding problem solving with computer simulations became a springboard towards initiating change in science learning.

To understand whether there was a significant difference between boys' and girls' performance in terms of higher-order thinking skills, an independent samples *t*-Test was performed. The results of the test showed that there was no statistically significant difference between male (M = 61.00; SD = 14.69) and female students (M = 58.57; SD = 13.78) in their scores for a post-test after studying chemical bonding problem solving with computer simulations, $t(33) = .497$; $p = .62$.

Discussion

The purpose of this study is to investigate how computer simulations can contribute to engaging students' active participation in new knowledge creation in chemical bonding problem solving with computer simulations. While learning chemical bonding problem solving was considered as difficult due to the topic abstractness, this study has shown that computer simulations can be used as a pedagogical tool to support student active engagement in knowledge construction. In fact, the findings of this study reveal that students learn in the conditions created by teachers/computer. Thus, this study suggests the following five actions (5As) that teachers can undertake to support student active engagement in chemistry learning with computer simulations:

1) *Action on contextual drivers*: computer simulations make learning happen in a special way, different from traditional teaching methods. *Action on contextual drivers* implies that the teacher needs to have a full picture of the learning practice based on expected outcomes of learning or on the unit competency, learning objectives, indicative content, and assessment criteria, and then organise learning activities accordingly. The teacher may prepare research questions to guide students work or formulate hypotheses to verify. Student may be requested to deal with a challenge, a case study, or a learning project. However, contextual drivers may vary from one topic to another and from one context to another.
2) *Action on the forms of participating in knowledge construction*: this study reveals four main forms of participating in knowledge construction with computer simulations: *self-reliance, peer collaboration-reliance, teacher-guided-reliance and strategic variation-reliance*. However, the study found no statistically difference between male and female students' preferences to engage in these forms. The findings indicates that these four forms can support

students to build new knowledge through collaboration and critical reflection around the object of learning (chemical bonding) and mediating tools (computer simulations) in support of gender equity.

3) *Action on multisensory connections*: Computer simulations can help students to create multisensory connections (*visible, audio, readable, motion and interactive*) with the object of learning enabling both boy and girl students to become actively engaged in learning chemistry through various settings. In fact, multisensory connections play a central role in bringing the object of learning to the student proximity. Finally, with multisensory connections conveyed by computer simulations, the lines between abstract concepts and chemical bonding reactions and processes become closely related as a virtual reality.
4) *Action on higher-order thinking skills*: This study suggests that students could construct higher-order thinking skills if they were given opportunities to explore computer simulations beyond indicative content proposed by the curriculum. These findings indicate that the teacher can take students' thinking to higher levels with computer simulations by allowing them some degree of autonomy and independence. For example, the teacher may invite students to see things in different ways, seek new solutions, make connections between concepts, experiment, search evidence and infer from them, analyse chemical reactions and processes, and apply new knowledge in a real-world situation.
5) *Action on the outcomes of learning*: students' opportunities to demonstrate the outcomes of chemical bonding problem solving with computer simulations can determine the way forward for the promotion of effective learning in STEM education. According to the findings, students were excited to report their achievements to the teacher and to other people outside their class including other students and the research team. The science club became an integral part of the school community engagement and an instrument to mobilise students around STEM education. Thus, the teacher needs to consider outcomes of learning for not only preparing, delivering, and assessing a lesson, but also for supporting individual and school community fulfilment.

Conclusion

The 5As that the teacher can perform to support active student engagement in chemistry learning with computer simulations are interdependent. For example, action on contextual drivers and that on outcomes of learning, though placed on opposite ends in the presentation, they are interrelated in practice. Outcomes of learning are defined at the beginning of a chemical bonding unit to guide the teaching/learning process, which takes place in specific contextual drivers. Action on contextual drivers determines the forms of participating in knowledge construction that are likely to occur. Thus, the teacher can plan how students will be involved in these forms in a way they maximise exploration of the object of learning through multisensory connections. These connections, on the turn, bring the object of learning to the students' proximity and facilitates the development higher-order thinking skills. These findings can contribute to improving the process of chemistry teaching/learning with computer simulations. On the other hand, they can be transferable to other STEM subjects taking into consideration contextual drivers under which computer simulations are implemented. In fact, the interplay between the 5As and their integration may contribute to building an effective pedagogy for STEM education in paving the way towards national sustainable development and innovative socioeconomic transformation. Finally, the 5As can offer a strategy to promote gender equity and equality in STEM education.

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