DE GRUYTER Chemistry Teacher International 2023; 5(3): 311–323

Research Article

Ayalew Temesgen Eticha*, Meseret Amde, Yiheyis Bogale and Deribachew Bekana

The effect of context-based close packing supported with the 3D-virtual model of crystals structure on students' achievement and attitude

https://doi.org/10.1515/cti-2022-0047
Received November 4, 2022; accepted April 28, 2023; published online May 16, 2023

Abstract: The major intention of this work was to evaluate the effect of using context-based close packing supported with 3D-virtual model on the concept of crystals structure on students' achievement and attitude. Accordingly, the study was conducted for two consecutive years and a total of 61 third-year undergraduate chemistry students have been participated. The nature of this study was quasi-experiment design and the sampled students were divided into intervention (24) and comparison (37) groups. The intervention group was treated with context-based close packing supported with the three dimensional virtual model (3D-virtual model), while the comparison group, covered the topic with the usual teaching-learning approach. The topic covered during the study period was crystals structure. At the end of the study, an identical post-test was given for both groups for comparative purposes. The result indicates that a significant difference was observed between the two groups (at $p < 0.05$). The intervention group students were more benefited than the comparison group. Besides, the response of intervention group students to the questionnaires and semi structured interviews indicates that the approach was effective in enhancing students' understanding of crystals structure concepts, and students have a positive attitude towards the approach.

Keywords: 3D-virtual model; crystal lattice; crystals structure; unit cell; visualization.

1 Introduction

Crystalline materials consist of periodically ordered arrays of atoms, molecules, or ions that can be packed in a regularly ordered fashion and represented by definite chemical formulas. Crystal chemistry deals with the principles of chemistry behind crystals or description of structure-property relations in solids such as: the symmetry and dimensions of the unit cell, the positions of atoms within the unit cell, the relation between crystals structure and physical or chemical properties, the factors that govern which type of structure is observed for a particular composition, and vice versa (Barke & Wirbs, 2002). It is one of chemistry fields recently getting attention due to its wealthy chemistry as well as the versatility of its applications (Torresi et al., 2020). Moreover, a number of researchers highlighted the importance of understanding crystals structure to predict properties of materials (Lenzer, Smarsly, & Graulich, 2019; Müssig et al., 2020). Take, for example, the properties of solids are defined by their structures and their interatomic or intermolecular forces. The fragility of salts, the ductility of metals and the hardness of inorganic polymers are direct consequences of their crystals structures. For instance, graphite and diamond exhibit different properties, due to their difference in structure of carbon (the π-bond

***Corresponding author: Ayalew Temesgen Eticha**, Chemistry, Haramaya University, Dire Dawa, Oromia, Ethiopia,
E-mail: ayalew_temesgen@yahoo.com
Meseret Amde, Yiheyis Bogale and Deribachew Bekana, Chemistry, Haramaya University, Dire Dawa, Oromia, Ethiopia

structure of graphite causes its electronic conductivity, whereas the localized bonds in diamond make it an electrical insulator) (Krauskopf et al., 2018; Lenzer et al., 2019).

Inline to this understanding the concept of atom/ion packing in a unit cells and the formation of crystal lattices is critical to understand and predict material properties. According to Lenzer, Smarsly, and Graulich (2019), without having solid understanding of structural features of a crystals, it is difficult to predict material properties. This is because, materials chemists predict and design materials with specific types of properties based on their crystals structure features. Some of these structural features depend on the arrangement and composition of several atoms/ions and molecules of the crystals such as: packing arrangement, lattice structure, and unit cell. Furthermore, a number of researchers reported that understanding the three-dimensional arrangement of unit cells in the solid is indispensable to realize the relation between chemical structure and materials' characteristic behavior (Dalacosta & Pavlatou, 2019; Lenzer et al., 2019; Urhahne, Nick, & Schanze, 2008). However, chemistry and material science students often have encountered problems in understanding chemical structure of substances (Dalacosta & Pavlatou, 2019; Fogarty, McCormick, & El-Tawil, 2018; Kelly, Heinert, Triplett, Baker, & Krause, 2010; Urhahne et al., 2008). Besides, a number of researchers reported the difficulty of the topic for students in general for a number of reasons such as: low priority given to visualizing skills in schools (Barke, Harsch, & Schmid, 2011; Dickenson, Blackburn, & Britton, 2020; Extremera, Vergara, Dávila, & Rubio, 2020); the way we taught the topic or using 2D-images, symbols and arrows (Gruber et al., 2020; Salta, Gekos, Petsimeri, & Koulougliotis, 2012; Taber, 2013); and difficulty to interplay the macroscopic representations into submicroscopic and symbolic levels (Kim & Paik, 2019) were some of them. These need special emphasis to design potential intervetion mechanisms which support chemistry students' to understand the basic concept of the topic and reduces students' difficulties. Furthermore, chemical educators highlighted the importance of representational mental models for understanding a wide range of chemical concepts taught in chemistry courses (Dean, Ewan, Braden, & McIndoe, 2019).

Understanding crystals structures required students to visualize and mentally represent the arrangement of atoms or ions and molecules in the 3D (Lenzer et al., 2019). Accordingly, chemists had put significant effort in developing molecular modelling tools, both virtual and physical models in their context to improve students' visualization of three-dimensional (3D) objects such as: VESTA (visualization for electronic and structural analysis) developed for 3D visualization of crystals structures and volumetric data using computers (Momma & Izumi, 2008); 3D structures animated software (Hsin-Kai & Priti, 2004); unit cell visualization tool (Gruber et al., 2020; Rodenbough, Vanti & Chan, 2015); and ball and stick models (Dickenson et al., 2020; Elsworth, Li, & Ten, 2017; Rossi, Benaglia, Brenna, Porta, & Orlandi, 2015; Sow, Udalagama, & Lim, 2013), and they reported context based developed intervention mechanisms were improved students' mental visualization of three-dimensional order of crystals structures, and improved students' metacognitive skills. Besides, Melaku and Dabke (2021) locally constructed (context-based) chemistry teaching matererials by interlocking toy building blocks (e.g., Lego) and used to depict chemistry concepts of Lewis structures, chemical bonding, conjugate acid-base pairs, types of chemical reactions, irregularity in ionization energy trends, and the decay of a radioactive isotope, and they reported that the approach was effective in enhancing students' visualization ability on these concepts.

In addition to different research reports on students' difficulty in crystals structure, from researchers' teaching experiences of different chemistry courses (>13 years of teaching experiences in the department of chemistry, at Haramaya University), they noted that many students faced challenge every year when they learned crystals structure concepts. Then, the researchers evaluated chemistry department students' exam scripts in the crystals structures prior to conduct this study, and they found that many students showed poor performance in the topic. Based on the review of reported research works (on the difficulty of students' in the crystals structure topic) and the observed current situations (students' low achievement in the crystals structure topics), it is important to design and implement intervention mechanisms to minimize students difficulty in crystals structure topics. However, there is no such special intervention mechanisms were developed and reported, specifically from developing counties where the technology development was limited and the problems remain unclear. Therefore, the major objective of this study was to develop context-based close packing of crystals supported with 3D-virtual model, implement in teaching crystal chemistry topic and evaluate its effect on students' achievement, and attitude. Furthermore, the study was aimed to answer the following research questions: Does the designed and implemented context-based close packing of crystals structure supported with 3D-virtual model improve students' achievement? To what extent the students were engaged/participated in the approach/interact with each other? What is students' attitude towards the approach?

2 Methodology

2.1 Description of the background of participants

The nature of this study was a quasi-experiment design which is commonly employed in the evaluation of educational programs when random assignment is not possible or practical. In this study 61 third-year undergraduate chemistry department students and two inorganic chemistry teachers were participated. The assignment of intervention and comparison groups was made based on their academic years to avoid the problem of contamination. Accordingly, all third-year students in the 2020 (N = 37) academic year represented comparison group while all third year students in 2021 (N = 24) academic year represented the intervention group. The participants of the study were deliberately selected from different academic years (comparison group students from 2020 academic year and an intervention group from 2021 academic year) and used for the comparative purpose to reduce the problem of contamination between the groups. Furthermore, if the participants selected from the same academic year and the treatments run parallel, they may share ideas with each other about the newly implemented *context based close packing of crystals structure supported with 3D-virtual model* on the crystals structure/solid state chemistry.

2.2 Research design

In this study, static group comparison design was used. In other words, two groups are chosen, one of the groups receives the treatment and the other does not receive the treatment. This is an attempt made to isolate the effect of the intervention on those selected research groups and other research groups who did not take the treatment. For this purpose, post-test was used to measure the difference between the two groups after the treatment. Therefore, static-group comparison or comparison group post-test-only design was summarized in the Table 1 below.

Table 1: Summary of the research design.

Intervention group	X	Pt_1
Comparison group	Y	Pt_1

where, X is treatment (context based close packing of crystals structure supported with 3D-virtual model), Y is conventional teaching approach/lecture method and Pt_1 is post-test.

2.3 Learning environment for intervention group students

In this study, both (i.e. comparison group and treatment group) group students work with small groups while the *context based close packing of crystals structure supported with 3D-virtual model structure* was utilized only for the intervention group students on crystals structure topics. Intervention group students were continuously encouraged to meet with their groups two times per week for 2 h each time (for four consecutive weeks). There was no such special treatment provided for the comparison group during the whole treatment period. The same chemistry lesson topics prescribed for the intervention groups were administered for the comparison groups using conventional method. Nevertheless, all necessary precautions were taken for ensuring certain standards and keeping the level of content and scope of coverage to both groups were similar (the teacher who give crystals structure topics; the course contents; post-tests; and the time taken to cover the topic).

2.4 Learning environment for comparison group students

The challenging problems from crystals structure topic were identified during the preliminary study. These problems were considered as triggered problems for both groups. Similar to intervention groups, comparison groups students were continuously encouraged to meet with their groups two times per-week for 2 h each time (for four consecutive weeks) and treated with conventional teaching approach without using *context based close packing of crystals structure supported with 3D-virtual model*. The instructor gave questions and assignments to assess students' academic achievement in the crystals structure topics that covered in actual class. Besides, the instructor assisted and encouraged students to work in a group and complete their group assignments during the tutorial session. The students dealt with scenarios involving several problems and tried to find appropriate answers to the problems. Then, the instructor guided and assisted the students in the place where they need explanations and extra help. In such way, all the students were kept active, and they were involved in the learning process. To maintain uniformity, the treatment time for both groups was the same. At the end of this treatment period, the same post-test was administered to both groups.

2.5 Context based close packing of crystals structure and 3D-virtual model

As mentioned in earlier section many students faced challenge with visualizing and mentally manipulating three-dimensional objects (visualizing crystal system of atoms/ions), and therefore, this context based crystal packing supported with 3D-virtual model were employed to help them conceptualize crystals structures. The context based crystal packing was designed by researchers by purchasing uniform multi-colored spherical balls-toys (from kids' toys supper market). Besides, the researchers installed 3D *virtual model* (crystal maker) software on physical laboratory computers of chemistry department. So that, students are able to build crystals structure of molecules, and ions/atoms based on the self-developed manual (by researchers) (Table 2). Therefore, IG students were practiced to build, display and manipulate different molecules of a given crystals structure from standard two-dimensional formula of inorganic chemistry books using context based approach and 3D virtual models, visualize the three-dimensional features of some selected crystals structure for a given molecules (Figure 1).

a) b) c) d)

Figure 1: Close packing model of (a) primitive cubic close packed structure, (b) tetrahedral holes, and, (c) octahedral holes from uniform multi-colored spherical ball-toys, (d) crystals structure of NaCl (Na, green, Cl = golden colour) constructed using crystal maker software (crystal system: cubic; lattice type: face-centered (F); space group symbol: F m −3 m; cell parameters: a = 5.6400 Å; b = 5.6400 Å; c = 5.6400 Å; atomic positions: Cl: 0.5, 0.5, 0.5; Na: 0, 0, 0 …).

Table 2: Activities conducted in context based close packing crystals structure and 3D-virtual model.

Activities conducted	Demonstrated concepts	Learning out comes
Build NaCl crystals structure	Students recognise the way atoms arranged in a given crystals structure, coordination numbers of NaCl	Students learn how to build crystals structures of NaCl and other salts using context based as well as with 3D-virtual model; internalize meaning of coordination numbers and coordination numbers of NaCl; build lattice type (face-centered cubic array of anions with an interpenetrating fcc cation lattice or vice-versa); distinguish crystal system of different salts (e.g. NaCl has cubic crystal system)
Model of hexagonal close-packing (hcp)	3D model of hcp crystals, recognize the types of hcp arrangement such as: ABAB, ABC ABC layer pattern, tetrahedral holes, octahedral holes, coordination numbers	Differentiate number of tetrahedral and octahedral holes in a given unit cell; recognize coordination numbers in crystal lattices
Model of cubic close-packing (ccp)	3D model of ccp crystals, recognition of the ABC layer pattern, tetrahedral holes, octahedral holes, coordination numbers	Identify number of tetrahedral and octahedral holes; distinguish ccp arrangement is identical to face-centered cubic (fcc) unit cells
Build CsCl crystals structure	The cesium ions (alternatively, the chloride ions) form a simple cubic unit cell. Coordination number both ions; cubic structure, Count the number of each ion per unit cell	Construct simple, bcc, or fcc unit cells for one kind of atom or ion, provides a 3D-visual aid for atoms in unit cells

2.6 Data gathering instruments

Relevant data were collected from the participants of the study through the use of multiple instruments (Chemistry achievement tests, questionnaire, interviews and observation).

2.6.1 Chemistry achievement tests: The performance of students' was evaluated with chemistry achievement post-test which was prepared from crystals structure topic. In detail, 30 items (10 multiple choice questions, 13 short answer questions and 7 matching items) were prepared and used for the purpose. Prior to use for wide-scale study, the content validity of the prepared chemistry achievement post-test was evaluated by two experienced inorganic chemistry teachers who taught the course for more than 13 years at University. They checked whether the prepared questions aligned with the course content and students' learning experiences. After their valuable comments, the researchers had made some rearrangements to ensure a high level of validity. Besides, the prepared post-test was distributed to pilot group students (not part of the samples of the study) and the reliability of the post-test was checked with Cronbach's alpha (0.83 with 117 pupils). Then, the post-test was administered for both groups at the end of the study period.

2.6.2 Questionnaires: A questionnaire was used to gather relevant information from intervention group students. For this purpose, two sets of questionnaires (open-ended and closed-ended) were prepared to collect data on whether the implemented context based close packing of crystals structure supported with 3D-virtual model improved students' achievement or not; and to assess students' attitude towards the approach in acquiring crystals structure concepts. Accordingly, the 7-items questionnaire was developed and used to explore intervention group students' achievement and attitude towards using context based close packing of crystals structure supported with 3D-virtual model, the significance, and constraints of the approach. The items were evaluated with a five-point rating scale ranges from strongly agree to strongly disagree and rescaled into three parts (agree, undecided, and disagree).

2.6.3 Interviews: Interviews were also used as data collecting instruments to get the views and opinions of students on the advantages and challenges of using context based close packing of crystals structure supported with 3D-virtual model in learning crystals structure topics. For the purpose, 5 students were randomly selected from intervention groups (one student from each group) and interviewed.

2.7 Observation

The researchers' (instructor/subject teacher) conducted observations while intervention group students attended the context based close packing of crystals structure supported with 3D-virtual model in crystals structure topics and evaluated the interactions held between students, the effectiveness of the method in acquiring the major concepts, and overall students' participation and its drawbacks.

2.8 Methods of data analysis

The collected data were analyzed quantitatively using descriptive statistics such as frequencies; percentage, mean, standard deviation, and inferential statistics (t-test). Furthermore, qualitative analysis method was employed for the data gathered through open-ended questionnaire, semi-structured interviews, and from class room observation.

3 Results and discussion

3.1 Comparison between intervention and comparison group students' post-test achievement

The *t*-test was used to decide whether the two groups (IG and CG) posttest achievement is statistically significant or not. The comparative analysis of post-test results showed a significant difference was observed between the two groups (Table 3).

The intervention group students performed better in the post-test exam than the comparison group students. This shows that an experience of using context based develeoped close packing crystals structure models and softwares enhance students' visualization and reason-out ability in crystals structures, and improve their achivement. A numerous studies have also revealed that there is a significant positive correlation between

Table 3: Comparison between intervention and comparison group students' on crystals structure post-test by using two sample *t*-test (N = 61).

Test	Groups	*N*	Df	Mean	SD	DoM	*t*-value	[a]*p*-Value
Posttest	Intervention group	24	59	19.66	6.82	6.98	3.78	0.0003
	Comparison group	37		12.68	7.18			

[a]At the 0.05 level, the difference of the population means are significantly different; N = number of intervention and comparison group students, P = probability, SD = standard deviation, Df = degree of freedom, DoM = difference of means.

spatial visualizing ability of students and success in science, technology, engineering, and mathematics courses (Fatemah, Rasool, & Habib, 2020; Hodgkiss, Gilligan, Tolmie, Thomas, & Farran, 2018; Khine, 2017).

3.2 Comparison between intervention and comparison group students' achievement on the targeted crystals structure questions

The researchers also analyzed the individual student exam scripts on selected targeted crystals structure questions and compared the analysis result between the two groups (Table 4).

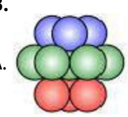
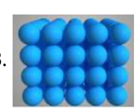
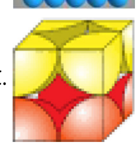
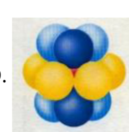
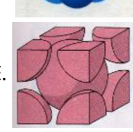
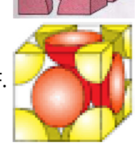
As can be seen in Table 4, questions 1–4 focussed on the basic concept of crystals structure such as: meaning of unit cell, crystal lattice, close packing in an ionic solid. For these questions only few comparison group students were gave correct and scientifically accepted meanings while majority of them didn't give the correct answers or in another word majority of comparison students failed to give scientifically accepted definitions and even they didn't distinguish the difference between the above-mentioned concepts compared to intervention group students. Surprisingly majority of comparison group students know the chemical formulas of NaCl, but they have no mental pictures of the close packing structures of this substance. We understood from their exam scripts, students only know the terminology or words than the full meanings of the crystals structures. Compared to intervention groups majority of comparison group students' answers were incomplete and inconsistent about the definition of the unit cell as a small repeating entity, basic structural unit, and fail to distinguish the difference between a unit cell and crystal lattice. Besides, they failed to give concrete and complete information about the spatial representation of unit cell and crystal lattice.

To answer these questions students should have a concrete understanding of the particulate nature of the matter in the level of the unit cell with spatial structures and their means of representation. However, understanding the spatial crystals structures of a given atom, ions, or molecules require concrete understanding of it at unit cell level which is the smallest repeating unit and shows the full symmetry of the crystals structure. When we describe crystals structures using unit cells, the size and shape of the unit cell and the positions of the atoms inside the cell are needed. For further illustration the researchers assisted intervention group students to construct and use the following context based close packing supported with 3D-virtual model approach (Diagram 1: (a) and (b) to distinguish the difference between a unit cell and crystal lattice).

This gives all the necessary information about the crystals structure, and it is important because a crystal is a solid material that contains atoms or groups of atoms arranged in a highly ordered structure described in three-dimensions and a crystal lattice describes the arrangement of these atoms in a crystal. In this regard, the approach helped IG students to visualize and understand the spatial structures of a given atom, ions, or molecules.

Questions number 5–7 were focused on coordination chemistry. For the above-mentioned questions, only a few CG students gave scientifically correct answers while majority of them do not have the concrete understanding the meaning of coordination number in different ionic solids; fail to determine coordination number of atoms in simple or primitive cubic close-packed structure, Body-centered cubic (bcc) structure, face-centered cubic (fcc) close packing structure, Hexagonal close pack (hcp) structure, and they failed to give example for each question. Before giving the right answers for these questions, students should primarily, be able to understand the unique properties of crystal solids, type of structure, and able to visualize the reasonable and acceptable

Table 4: Comparison of intervention and comparison group students' achievement on targeted crystals structure questions.

S. No.	Questions		*f* (%) CG	% (*f*) of IG
1.	What is unit cell? Please give brief definition with example (consider NaCl or other if you like)		15(40.54)	21(87.50)
2.	What is a crystal lattice? Please give brief definition		14(37.84)	18(75.00)
3.	What is close packing in an ionic solid? Please give a brief definition with example (i.e. NaCl as an example or other if you like)		9(24.32)	12(50.00)
4.	What is meant by the term coordination number in ionic solids? Please give brief definition		5(13.51)	11(45.83)
5.	What is the coordination number of atoms in a/an			
A.	Simple or primitive cubic close packed structure?		6(5.41)	8(33.33)
B.	Body–centered cubic (bcc) structure?		6(16.22)	15(62.50)
C.	Face centered cubic (fcc) close packing structure?		3(8.11)	11(45.83)
D.	Hexagonal closest packed (hcp) structure?		4(10.81)	13(54.17)
6.	How is a coordination number for a given an ionic solid determined? Please give brief explanation by considering NaCl (or other if you like).		8(21.62)	10(41.67)
7.	What is tetrahedral hole? Please give brief definition		14(37.84)	19(79.17)
8.	How many tetrahedral holes are there in the fcc?		4(10.81)	8(33.33)
9.	What are the octahedral and tetrahedral sites in close packed arrangement? Please give brief explanation		4(10.81)	9(37.50)
10.	What is the difference between hexagonal closed packed (hcp) structure and cubic closed packed (ccp) structure? Please give brief explanation on the differences		2(5.41)	13(54.17)
11.	What is the difference between body centered cubic and face centered cubic? Please give brief explanation on the differences		5(13.51)	11(45.83)
12.	Please list the name of all seven crystal lattice systems with their unit cell and their differences		1(2.70)	8(33.33)
13.	Please list the name of all seven crystal lattice systems, their differences and give at least one example for each		1(0.94)	7(29.16)
Match the structures given under B with the type of arrangement given under A (more than 1 answer is possible).				
	A.	**B.**		
14.	___ABC,ABC… type structure	A. 	9(24.32)	16(66.66)
15.	____A-A-A type arrangement	B. 	7(18.9)	18(75)
16.	____Hexagonal close pack	C. 	8(21.62)	15(62.5)
17.	____AB-AB type arrangement	D. 	11(29.72)	19(79.16)
18.	___Simple or primitive cubic	E. 	12(32.43)	17(70.83)
19.	___Body centered cubic	F. 	9(24.32)	14(58.33)
20.	___Face centered		10(27.02)	88(62.5)

f = frequency, CA = Correct Answer, % = Percentage of respondents, *f* = frequency of respondents, IG = intervention group, CG = Comparison Group.

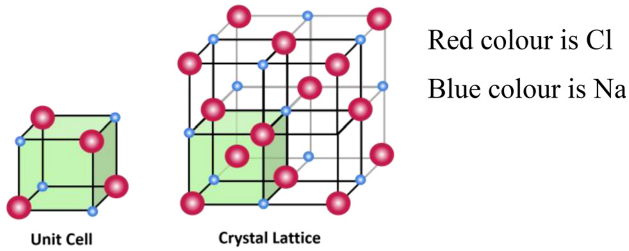


Diagram 1: (a) Example of unit cell, and (b) example of crystal lattice.

structural representations of each crystal packing structure. In this regard, the researchers assisted intervention group students to construct crystal structure of atoms/ions or molecules using context based close packing supported with 3D-virtual model. Accordingly, different conceptual representation models of crystals structure systems used during intervention periods were indicated in Figure 2.

Questions number 8–12 were focused on types of close packing and associated properties (i.e., types of holes formed or octahedral and tetrahedral etc.). For the above-mentioned questions, majority of comparison group students failed to clearly explain the difference between hexagonal closed packed (hcp) and cubic closed packed (ccp) structures, failed to explain the difference between body-centered and face-centered cubic while only few students were successfully explained scientifically correct answers. It is evident from students exam scripts, some of CG students tried to give their answers based on the framework of their pre-instructional understanding of words like hexagonal = six angle, cube = equal size etc. not based on their literal meaning of crystals structure or visual arrangement of atoms/ions and molecules, and its associated properties.

For question 13, only one student listed the name of the entire seven crystal lattices (Cubic, Tetragonal, Orthorhombic, Trigonal, Hexagonal, Monoclinic, and Triclinic). Majority of CG as well as IG students were failed to clearly articulate the difference between the seven lattice structures and the possible unit cell they have. However, number of IG students who gave correct answer was better than number of CG students. This indicates that still students have difficulty with the topic and it needs further emphasis to minimize students' difficulty.

Questions 14–20 were focused on the assessment of students' ability to describe the crystals structures using a close packing approach. The crystals structures of a large number of alloys, metals, and inorganic compounds can be described geometrically in terms of a close-packing arrangement of atoms/ions in equal size spheres, held together by interatomic forces. However, only a few CG students gave correct answers for these questions while the majority of them failed to describe the types of crystal packing; failed to distinguish hexagonal close pack from cubic close packing, face-centered cubic from body-centered cubic, and type of hexagonal arrangement. Conversely, the majority of IG students describe the types of crystal packing and hexagonal arrangement,

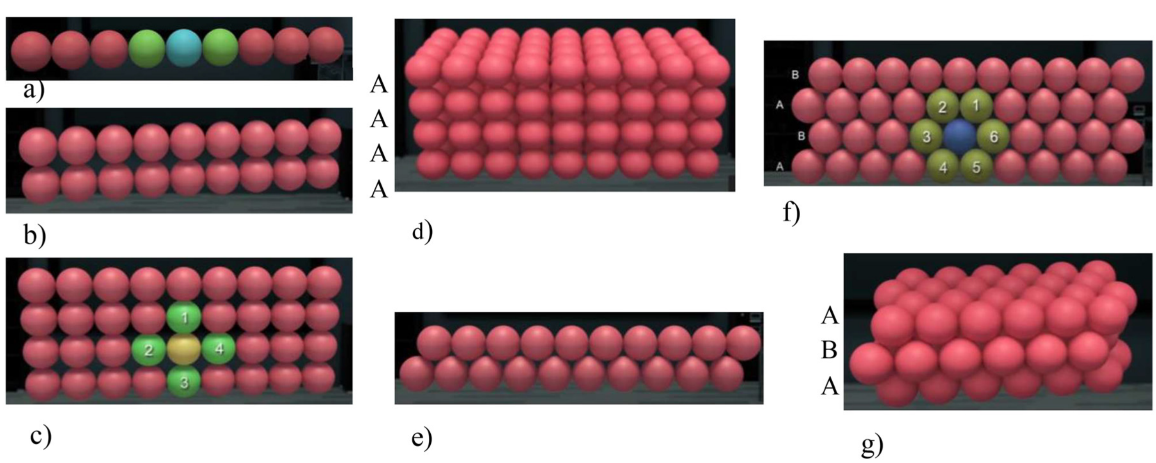


Figure 2: (a) In one dimensional spheres; (b) two dimensional close packing; (c) square close packing from two-dimensional; (d) three-dimensional square close packing from two-dimensional layers (AAA … type); (e) hexagonal close packing in two dimensions; (f) hexagonal close packing from two dimensions (ABAB … type); (g) three-dimensional hexagonal close packing from two dimensions (ABAB … type).

distinguished the types of hexagonal close pack from cubic close packing, and face-centered cubic from body-centered cubic. It is evident from students' exam scripts that many IG students are good in recall of facts, knowledge and terminologies while majority of CG students have difficulty in transform and interpret theoretical concept to visual or geometrical aspects of structures and vice versa.

In general, we can conclude from the above observed students' exam script analysis, many intervention group students have better understanding the scientific meaning of unit cell and crystal lattice, better in visualizing arrangement of atoms/ions and molecules of crystal systems or in three-dimensional forms; have better in transforming the symbolic representation to macroscopic, microscopic/ionic representation to macroscopic and vice-versa; easily distinguished face-centered cubic from body-centered cubic; and type of hexagonal arrangement compared to comparison group student. A number of researchers also reported that the combination of three-dimensional representations and activities with three-dimensional models enhance students' mental representations and understanding crystals structures futures (Fogarty et al., 2018; Melaku & Dabke, 2021; Rossi et al., 2015; Sunderland, 2014).

3.3 Survey of attitude of intervention group students

The researchers assessed intervention group students' attitude towards context based close packing of crystals structure supported with 3D-virtual model at the end of the course using close ended, open ended and interview questions. The analysis result of the close ended questions given in Table 5.

Table 5: Questions responded by intervention group students on using context based close packing of crystals structure supported with 3D-virtual model learning experience.

No.	Statements	% of respondents		
		Positive	Neutral	Negative
1	Building structure of different types of crystals system with my colleagues enhanced my understanding	91.66	4.16	4.16
2	My group members discussed together and helped each other during the approach	75	16.66	8.33
3	I had good time during the approach	100	–	–
4	The approach helped me to score better results in this topic	79.16	20.83	–
5	The approach helped me to visualize the 3D crystals structure of atoms/ions and molecules	79.16	12.5	8.33
6	The approach helped me to recall and memorize the structure of molecules easily	91.66	8.33	–
7	Building different solid crystals structures with the approach helped me to understand and predict their properties	70.83	25	4.16

Generally, as can be seen from Table 5, majority of intervention group students have positive attitude toward using context based close packing of crystals structure supported with 3D-virtual model which helped them in understanding the concepts. They also appreciated the contribution of the approach in bringing students together which develop the experience of working together in addition to academic achievement.

3.4 Interview with intervention group students

The researchers opened the session by welcoming participants and introduced the objective of the interview, and gave chance to each interviewee to introduce his/her name. Then, the interviewer proceeds to his questions (the following interview was held with one randomly selected intervention group student).

> Researcher: I would like to ask you some questions about using context based close packing of crystals structure supported with 3D-virtual model we used during our class or in learning crystals structure topic and the experiences you had during the class. So can you tell me a little bit about your experiences with the approach in your class?

Student 1: Yes, I do.

Researcher: Ok, how do you see learning crystals structure topic (constructing different crystal system) with the approach?

Student 1: Yeah, learning crystals structure topic with such approach is good and I believe that it is useful, because what we learned during the session was like a practical (i.e. learning by doing, construct different structures from simply small plastic balls, draw on the computer and compare with context based constructed crystals structures by rotating, etc), was too memorable. The session was interesting and different from other learning sessions.

Researcher: What do you mean the session was different from other sessions? What made it different from other sessions?

Student 1: Yeah, from my view I got it different because I didn't learn other chemistry courses in such way (by constructing with local available was well as practicing with software). I don't have such experience before, also I think, this is everyone's first-class to learn crystals structure topic with such approach (manipulate things with hands, constructed and rotate the 3D-structure of different ions and molecules on the PC screen and observed their structures etc. I can say a lot of things more.

Researcher: In your opinion, do you think learning crystals structure with such approach would help you in your studying, and to achieve a good result in crystals structure?

Student 1: Definitely!

Researcher: How? Please could you explain about it?

Student 1: Ok, learning crystals structure topic with the approach helped me to understand things in a better way. For example, as I said earlier, I don't have experience of construct different molecules from locally available materials as well as with such software. But, this class helped me to do so i.e. rotate and simulate the three-dimensional structure of the molecules, identify the difference between molecules, and easily visualize the crystals structure of different molecules. For example, to decide the configuration of any molecules, I always tried to understand the 2D structures drawn on the text book and visualizing the hypothetical structure of the compound. But, now during this session, I realized that it is possible to construct and visualize the hypothetical 2D drawings from a textbook with such approach. Even, we discussed with my colleagues about things we confused on and fixed as soon without any further assistance from teacher or technician.

Researcher: Do you think working together is useful in such case?

Student 1: Definitely! We worked in groups or with my colleagues throughout the class and we enjoyed it a lot. I gained a lot of things from working together. I can say working with group is very important in such case to share ideas and tackle problems which might be difficult to understand alone. For example, if I don't understand something, I need to talk to my friends and observe how they solve that problem. Here in the crystals structure class, sometimes we faced similar challenges in identifying the correct configuration of a given molecules but we discussed together with my colleagues and easily identify the correct structures which represent the designers of molecules. In my opinion, working together is better than working alone. I felt, construct the structure of a given molecule alone, might be misrepresented the correct structure of the molecules and for me better to work together for better understanding. Even, I realized the importance of working together at the end of the class.

Researcher: What skills, if any, do you think you have gained from using context based close packing of crystals structure supported with 3D-virtual model?

Student 1: Well, I would say that I enjoyed and learned many skills such as using 3D-virtual model software which has numerous applications, and visualizing the structure of different molecules.

The analysis of semi-structured interview indicates that all of the interviewed participants gave a positive response or they appreciated the way they learned the topic. The researchers categorized their responses into three main ideas. The first point deals with the importance of context based close packing of crystals structure supported with 3D-virtual model in enhancing student visualization ability, help students to recognise the way atoms arranged in a given crystals structure (pattern), and recognize the unit cell and number of holes (tetrahedral and octahedral holes). The other point which the respondents specifically emphasized is the importance of group work which creates an opportunity for students to discuss with each other. The last point the respondents accentuated was the suitability (good-looking) of the approach. Based on points raised above, it is possible to summarize the importance of context based close packing of crystals structure supported with 3D-virtual model to visualize and understand the nature and structure of crystal molecules/ions explicitly which is basic to understand the properties of materials. The skills and experiences they gained from the approach is in agreement with other researchers' findings (Bortnik, Stozhko, & Pervukhina, 2021; Chiu, 2021; Wu & Shah, 2004).

3.5 Summary of observation results

The researchers conducted observation while intervention group students practicing their activities using physical and virtual model to evaluate overall students' activities during the session such as: observing and evaluating the interactions held between students, conduciveness of the method to users, students' interest and participation, students time usage, and its drawback (Table 6).

During the observation period, the researchers were evaluated intervention group students' interaction within the group and across the group, and concluded that the approach is effective in creating conducive learning environment or there is a positive interaction between the students (discussed together and helped each other). The researchers also, evaluated the effectiveness of the method in acquiring crystals structure concepts and they found that the approach is better in improving students' visualizing ability (visualize atoms/ions arrangement orders). It familiarizes students with working with computer (rotate 3D structure of the molecules and create mental representation), help teachers to assess his/her students' limitation/gap of understanding crystals structures (used as assessment tool to identify students' visualization ability and properties of crystal solids).

The researchers explored the time students spent on the approach construction and discussion on the constructed model. When we compare the time students spent on constructing context based close packing of crystals structure supported with 3D-virtual model activity with discussion about the constructed model, majority of students spent 60 % of their time on discussion about the structure-property of the constructed model (students touched and moved the constructed structure, occupation sites, identify the coordination number, compare the types of arrangements, etc.) while 40 % of their time on the reading pre-instruction and construction of the model (gluing the balls, arrangement, interchange the positions and modify the arrangements etc.). Therefore, the time students spent on the discussion about the relation between crystals structure and physical or chemical

Table 6: Summary of observation result.

Evaluated activities	Observation and feedback from researchers
Interactions held between students	– There is a positive interaction between the students (discussed together and helped each other) – Students shown good motivation and participation – The approach helps teachers to make their classes more interactive, and interesting
The effectiveness of the method acquiring crystals structure concepts	– It familiarizes students with computer, and 3D structure of the molecules – It helps students to rotate and visualize atoms/ions arrangement orders – Help teachers to assess his/her students' limitation/gap of understanding crystals structures (used as assessment tool to identify students' visualization ability)
Students' interest and participation	– Students shown good participation in drawing d/t structures and display the 3-D (actively participated) – It makes learning enjoyable for students
Students time usage	– Students spent 40 % of their time on the reading pre-instruction, organizing materials, and construction of the model – Students spent about 60 % of their time on discussion about the structure-property of the constructed model
Drawback of the method	– It requires adequate training and facilitation at the beginning (i.e. relation between the observer and the observed) – It requires computer resources – Some students have limitation of computer skills

properties is much higher than the time spent on pre-instruction and construction of the models. In all these processes the researchers facilitates and guides students in the process of independent learning and students also shown good participation in constructing the given crystals structures which makes the learning enjoyable.

Based on the result of the study, the researchers concluded that using context based close packing of crystals structure supported with 3D-virtual model would entices learners' interest, enhance students interaction within the group and across the group, improve students' visualizing ability and understanding, and enhance their participation which is in agreement with the previously reported findings (Fogarty et al., 2018; Shamsuddin, Adamu, Muhammad, & Oluwatoyin, 2018; Sunderland, 2014).

Conclusions

The result of the study revealed that, IG students have better in visualizing crystals structure of atoms/ions and molecules. In other word, context based close packing of crystals structure supported with 3D-virtual model is more beneficial to visualize the crystals structure, advances experience of working together, enhance students' achievement and understanding; and reduce students difficulty towards visualization. The approach helped students to explain the difference between hcp and ccp structures, the difference between body-centered and face-centered cubic, recognize AAA, ABAB, ABC… layer pattern, tetrahedral holes, octahedral holes, coordination numbers, and this in turn improve their achievement. The responses to the questionnaires and interviews gathered from intervention group students also indicates that context based close packing of crystals structure supported with 3D-virtual model topic was effective in acquiring crystals structure concepts and students have positive attitude towards the approach.

Author contributions: All the authors have accepted responsibility for the entire content of this submitted manuscript and approved submission.
Research funding: None declared.
Conflict of interest statement: The authors declare no conflicts of interest regarding this article.

References

Barke, H. D., Harsch, G., & Schmid, S. (2012). Structure-oriented approach in chemical education. In *Essentials of chemical education*, Berlin, Heidelberg: Springer (pp. 291–319). https://doi.org/10.1007/978-3-642-21756-2_10.

Barke, H. D., & Wirbs, H. (2002). Structural units and chemical Formulae. *Chemistry Education: Research and Practice*, *3*(2), 185–200.

Bortnik, B., Stozhko, N., & Pervukhina, I. (2021). Context-based testing as assessment tool in chemistry learning on university level. *Education Sciences*, *11*(8), 450.

Chiu, W.-K. (2021). Pedagogy of emerging technologies in chemical education during the era of digitalization and artificial intelligence: a systematic review. *Education Sciences*, *11*(11), 709.

Dalacosta, K., & Pavlatou, E. A. (2019). Using cartoons agents and 3D visualizations based on HTML5 for improving learning in crystal structures in engineers. *Computer Applications in Engineering Education*, *28*(1), 1–12.

Dean, N. L., Ewan, C., Braden, D., & McIndoe, J. S. (2019). Open-source laser-cut-model kits for the teaching of molecular geometry. *Journal of Chemical Education*, *96*(3), 495–499.

Dickenson, C. E., Blackburn, R. A., & Britton, R. G. (2020). 3D printing workshop activity that aids representation of molecules and student comprehension of shape and chirality. *Journal of Chemical Education*, *97*(10), 3714–3719.

Elsworth, C., Li, B. T., & Ten, A. (2017). Constructing cost-effective crystal structures with table tennis balls and tape that allows students to assemble and model multiple unit cells. *Journal of Chemical Education*, *94*(7), 827–828.

Extremera, J., Vergara, D., Dávila, L. P., & Rubio, M. P. (2020). Virtual and augmented reality environments to learn the fundamentals of crystallography. Crystals, *10*(6), 1–18.

Fatemah, A., Rasool, S., & Habib, U. (2020). Interactive 3D visualization of chemical structure diagrams embedded in text to aid spatial learning process of students. *Journal of Chemical Education*, *97*(4), 992–1000.

Fogarty, J., McCormick, J., & El-Tawil, S. (2018). Improving student understanding of complex spatial arrangements with virtual reality. *Journal of Professional Issues in Engineering Education and Practice*, *144*(2), 04017013.

Gruber, C., James, A., Berchtold, J. T., Wood, Z. J., Scott, G. E., & Alghoul, Z. (2020). Interactive unit cell visualization tool for crystal lattice structures. *Journal of Chemical Education*. *97*(7), 2020–2024.
Hodgkiss, A., Gilligan, K. A., Tolmie, A. K., Thomas, M. S., & Farran, E. K. (2018). Spatial cognition and science achievement: The contribution of intrinsic and extrinsic spatial skills from 7 to 11 years. *British Journal of Educational Psychology*, *88*(4), 675–697.
Hsin-Kai, W., & Priti, S. (2004). Exploring visuospatial thinking in chemistry learning. *Science Education*, *88*(3), 465–492.
Kelly, J., Heinert, K., Triplett, J., Baker, D., & Krause, S. (2010). *Uncovering-and-repairing-atomic-bonding-misconceptions-with-multimodal-assessment-of-student-understanding-in-an-introductory-materials-course*. Clearing up student misconceptions in materials. Retrieved from https://peer.asee.org/16354.
Khine, M. S. (2017). *Spatial cognition: Key to STEM success. Visual-spatial ability in STEM education: Transforming research into practice* (pp. 3–8).
Kim, S. K., & Paik, S.-H. (2019). Hands-on experiment to verify consistency from bulk density to atomic and ionic radii with lumps of metals and ionic compounds. *Journal of Chemical Education*, *96*(10), 2271–2278.
Krauskopf, T., Muy, S., Culver, S. P., Ohno, S., Delaire, O., Shao-Horn, Y., Zeier, W. G. (2018). Comparing the descriptors for investigating the influence of lattice dynamics on ionic transport using the superionic conductor Na3PS4-xSex. *Journal of the American Chemical Society*, *140*(43), 14464–14473.
Lenzer, S., Smarsly, B., & Graulich, N. (2019). Making it clear: Exploring crystal structures by constructing and comparing see-through models. *Journal of Chemical Education*, *96*(8), 1630–1639.
Melaku, S., & Dabke, R. B. (2021). Interlocking toy building blocks as modules for undergraduate introductory and general chemistry classroom teaching. *Journal of Chemical Education*, *98*(7), 2465–2470.
Momma, K., & Izumi, F. (2008). VESTA: A three-dimensional visualization system for electronic and structural analysis. *Journal of Applied Crystallography*, *41*(3), 653–658.
Müssig, J., Clark, A., Hoermann, S., Loporcaro, G., Loporcaro, C., & Huber, T. (2020). Imparting materials science knowledge in the field of the crystal structure of metals in times of online teaching: A novel online laboratory teaching concept with an augmented reality application. *Journal of Chemical Education*, *97*(9), 2643–2650.
Rodenbough, P. P., Vanti, W. B., & Chan, S.-W. (2015). 3D-printing crystallographic unit cells for learning materials science and engineering. *Journal of Chemical Education*, *92*(11), 1960–1962.
Rossi, S., Benaglia, M., Brenna, D., Porta, R., & Orlandi, M. (2015). *Three dimensional (3D) printing: A straightforward, user-friendly protocol to convert virtual chemical models to real-life objects*. ACS Publications.
Salta, K., Gekos, M., Petsimeri, I., & Koulougliotis, D. (2012). Discovering factors that influence the decision to pursue a chemistry-related career: A comparative analysis of the experiences of non scientist adults and chemistry teachers in Greece. *Chemistry Education: Research and Practice*, *13*(4), 437–446.
Shamsuddin, I. M., Adamu, A. M., Muhammad, A., & Oluwatoyin, O. R. (2018). Influence of using ball-and-stick models in teaching nomenclature to SS 3 chemistry students in Sabon Gari local Government Area of Kaduna State. *Education Quarterly Review*, *1*(1), 18–27.
Sow, C., Udalagama, C. N., & Lim, G. (2013). Teaching crystal structures using a transparent box with tennis balls. *Journal of the NUS Teaching Academy*, *3*(1), 18–33.
Sunderland, D. P. (2014). Studying crystal structures through the use of solid-state model kits. *Journal of Chemical Education*, *91*, 432–436.
Taber, K. S. (2013). Revisiting the chemistry triplet: Drawing upon the nature of chemical knowledge and the psychology of learning to inform chemistry education. *Chemistry Education: Research and Practice*, *14*, 156–168.
Torresi, S., Bou-Gil, A., D´Anna, M., Escámez-Gutiérrez, P., Peña-Recuenco, N., Chouli, S., Serna-Gallén, P., Beltrán-Mir, H., Cordoncillo, E. (2020). A way to understand the solid-state chemistry for high level education students: The case of a ceramic pigment. In *EDULEARN20 Conference 6th–7th July 2020* (pp. 974–981).
Urhahne, D., Nick, S., & Schanze, S. (2008). The effect of three-dimensional simulations on the understanding of chemical structures and their properties. *Research in Science Education*, *39*(4), 495–513.
Wu, H.-K., & Shah, P. (2004). Exploring visuospatial thinking in chemistry learning. *Science Education*, *88*(3), 465–492.