Journal of
Virtual Worlds Research
jvwr.net ISSN: 1941-8477

Pedagogy
Taking Stock and Looking Forward

December 2018 (Part 1)
Volume 11 No. 3

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jvwresearch.org ISSN: 1941-8477

Volume 11, Number 3
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December 2018

Representations of Novice Conceptions with Learner-Generated Augmentation: A Framework for Curriculum Design with Augmented Reality

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Abstract

This paper describes how learner-constructed Augmented Reality was used in an intervention among science undergraduates in Taiwan, to help their course instructor have a clearer understanding of how novices in chemistry approach and seek to make sense of key concepts in this discipline.

The intervention was carried out in the latter half of 2018 using a freely-available app which could be downloaded to any smartphone or tablet which supports Augmented Reality. The undergraduates were introduced to the app and used its affordances as part of their course activities in chemistry.

We have termed the pedagogical approach described in this paper as Learner-Generated Augmentation. The intervention and pedagogical approach reported in this paper has potential implications on the design and adoption of subsequent applications of Augmented Reality in contexts of learning; this is because – at the very least – the approach described can be implemented at a lower cost of time, money, and manpower than earlier efforts at integrating Augmented Reality in to learning designs.

Results of surveys administered to participants are shared in this paper, as are samples of learner-constructed artifacts in Augmented Reality. It is hoped that the work reported might form the basis of subsequent studies in other disciplinary domains.

1. Introduction / Background

Augmented Reality is a relatively new field in terms of the design of learning environments. For much of 2017 and early 2018, teachers and curriculum designers interested in exploring this field were dependent on engaging digital content creators and software developers in designing such learning experiences for students.

In May 2018, both Google and Facebook independently released cross-platform versions of their respective software which afforded the everyday user (teachers and learners) to sketch in three-dimensions within their local environments, using nothing but their fingers on their smartphones.

In recognition of the possibilities represented by this new paradigm, the study described in this paper sought to help course instructors at college-level chemistry explore and understand the affordances of Augmented Reality in the learning of science, specifically in chemistry.

The study describes a collaboration between teams from the National Institute of Education in Singapore and the National Pingtung University in Taiwan. Through this collaboration, a study was conceptualized and enacted among undergraduates for the July – December semester in 2018.

The purpose of the pilot was to help teachers and course instructors have a clearer understanding of how novices in chemistry approach and seek to make sense of key concepts in these disciplines, such as the structure of organic molecular chains.

The intervention was carried out using a freely-downloadable app which could be downloaded to any smartphone or tablet which supports Augmented Reality, generally includes devices manufactured since 2016. During the study, the undergraduates were introduced to the app and used its affordances as part of their course activities in chemistry.

This pedagogical approach – which we have dubbed Learner-Generated Augmentation – is distinct from the majority of learning interventions using Augmented Reality to date. Specifically, the majority of learning interventions with Augmented Reality are designed from the perspective of using the technology to exemplify the concepts to be learned – such as Fleming's Right-hand/Left-hand and right-hand-grip rules in physics and the structure of organic molecular chains in chemistry.

For this project, the curriculum design paradigm is from the diametrically opposed perspective of tasking the learners (and not the domain experts) to depict such conceptual representations, using the augmentations afforded by Augmented Reality. In other words, instead of using Augmented Reality to help learners visualize the concepts, the technology is used to afford them the ability to sketch and represent their naïve and evolving conceptions for themselves.

In this way, their conceptions and intuitions about the respective topics are made more visible to their teachers and their peers, thereby making collaborative dialogue around their misconceptions more meaningful.

2. Literature Review

2.1. A Phenomenological Approach to Representation

The study reported in this paper has roots in the work of Husserl and his writings on phenomenology. Husserl's earliest writings on phenomenology - *Reine Phänomenologie* - are now more than a century old. They remain extremely relevant to the issues facing the learning sciences today.

In 2009, the lead author shared a curriculum design framework on the affordances for learning of immersive environments. In the Six Learnings framework (Lim, 2009), six primary ways in which virtual worlds and immersive environments may be used for learning are described, one of which is Learning by Building:

"By 'Learning by Building' is meant the learning that results from tasks that require the learners to build objects and/or script them. Such activities could potentially involve the demonstration of mathematical understandings of trigonometry and physics, the learners' sense of aesthetics, as well as their grasp of the logical algorithmic flows inherent in a scripting language." (Lim, 2009: 8)

An example of such a building task is shown in the Figure 1 below, which shows an avatar 'rezzing' (reifying – giving form to) a 'prim' (a basic building block) in the virtual world of Second Life.

Figure 1: 'Rezzing' a prim in Second Life.

In 2009, it was only possible to reify such objects from no pre-existing physical resources, through a virtual world or immersive environment.

In 2018 however, because of efforts of companies such as Facebook and Google in Augmented Reality, such intentional reifications of Husserl's 'objects of the mind' (Husserl, 1982) are now possible into the actual local environments of the learner.

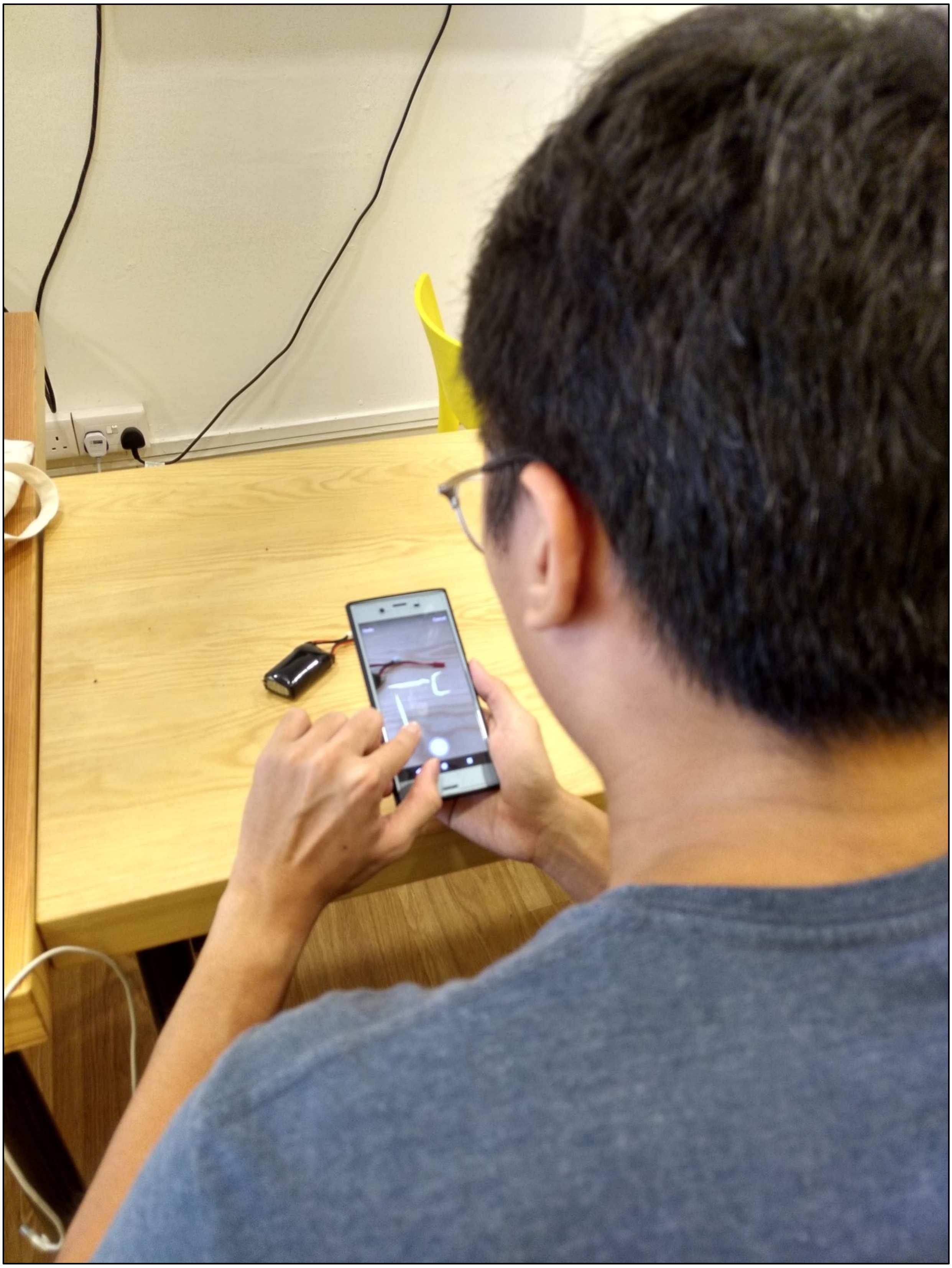

Figure 2: Sketching a three-dimensional form with Augmented Reality

Thus, Figure 2 above shows a learner using his finger (in much the same way as the avatar in the preceding figure) to 'rez' (or reify) an object (in this case, Fleming's Left-hand rule, where the 'C' denotes current) into his physical environment (as shown by the object on the desk) simply by sketching it.

This affordance for learning – in which the learner is able to reify an intentional object in its proper presentation (Brentano, 1973, pp. 54), in his/her local environment, from no pre-existing resources – has never been possible, till the present day.

The implications of this affordance as windows of intersubjectivity into the minds of learners are significant. In his earlier work on Disciplinary Intuitions, Lim (2015, pp. 165) expressed his thoughts in the following way:

> "The design of curriculum for formal learning environments often presumes upon (whether explicitly or implicitly) the intuitions that learners bring to the table. These intuitions - to the extent that they exist in the first place - may have been developed through personal experience and prior knowledge, often through non-formal learning such as play. Such intuitions are, however, tacit by definition, and their qualities would vary from learner to learner. Both this tacit nature and this heterogeneity work against the explicit recognition of the role that such intuitions play in the curriculum design of more formalised learning environments; yet they are of critical importance - at the very least in terms of shaping the pre- and misconceptions that learners have, and consequently the likelihood that what is learnt endures beyond the immediate formalized experience."

At its heart, then, Disciplinary Intuitions is fundamentally phenomenological in its orientation. The central problematic articulated by Disciplinary Intuitions is that between phenomenology's 'lived experiences' and curriculum design. A curriculum designed from the perspective of Disciplinary Intuitions recognizes the diversity of such lived experiences and attempts to facilitate greater intersubjectivity among learners.

Conceptualized in this way, Disciplinary Intuitions may therefore be thought of as innate computational modules of mind (Pinker, 1997, pp. 32) which are in the process of being exercised and developed as the learner interacts with his or her external environment.

Disciplinary Intuitions and the Six Learnings framework are elaborated upon at http://sites.google.com/site/disciplinaryintuitions/

The study described in this paper is an attempt to help learners give form to what has generally remained tacit, through the approach of Learner-Generated Augmentation. The study seeks to do so by describing an intervention in Chemistry Education.

2.2. Representations in Chemistry and the Challenges to Learning Thereof

In chemistry, molecular and atomic structures are depicted using diagrams that illustrate the atoms that comprise them and their organization in space (Hegarty, Carpenter, & Just, 1991, pp. 57).

2.2.1. Valence Shell Electron Pair Repulsion (VSEPR) theory

VSEPR theory is a model that is used to predict the shape of a molecule. Since the shape of the molecule will determine the physical and chemical properties of the compound, it is essential that novices understand this model. However, it is extremely difficult for the novice to visualize a three-dimensional (3D) molecule from two-dimensional (2D) paper. Therefore, common teaching aids are videos or physical models for students to aid visualization of the molecules in three dimensions. However, these teaching aids are only pre-built models, while the student may require help in visualizing other molecules. Furthermore, students may not be able to access those tools conveniently.

2.2.2. Optical Isomerism

In organic reactions, where the end product has molecules with a Chiral carbon (C-atom with four different groups attached,) there will, very likely, be optical isomers. Optical isomers have the ability to rotate the plane of polarization of light. Therefore, it is important for a novice to understand optical isomerism in order to account for the various end products and their physical properties. However, it is challenging for a novice to visualize that the two three-dimensional molecules are in fact different molecules and rotating them will not become the other molecule. Common teaching aids are using color-coded diagrams and physical models of the molecules. However, these diagrams will not provide students with an embodied visualization of the molecule.

Wu and Shah (2004) suggest that there is a continuum of different forms of chemical representation/illustration which, while abstract, convey varying levels of analogical information.

For example, Structural and Skeletal formulas of molecules depict the individual atoms involved in the molecules and the type and number of bonds between them (Figures 3 and 4 respectively). They are also able to show the shape of the molecule and the arrangement of atoms in relation to each other. However, these forms of illustrations are limited in their ability to depict the VSEPR theory, which discusses the geometry of molecules with reference to the number of electron pairs surrounding its central atoms (Jolly, 1984).

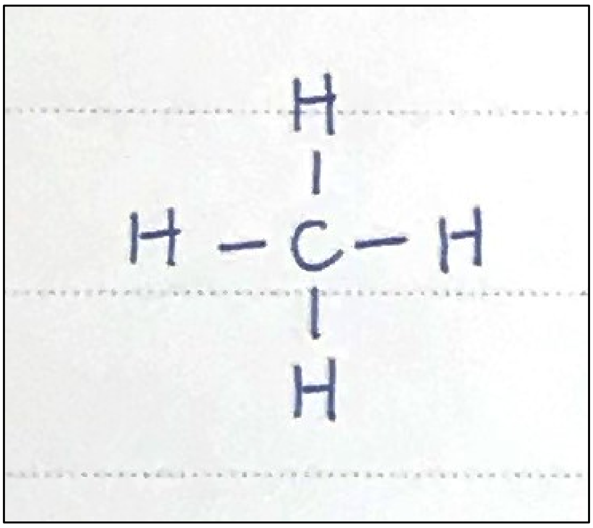

Figure 3: Structural formula for methane

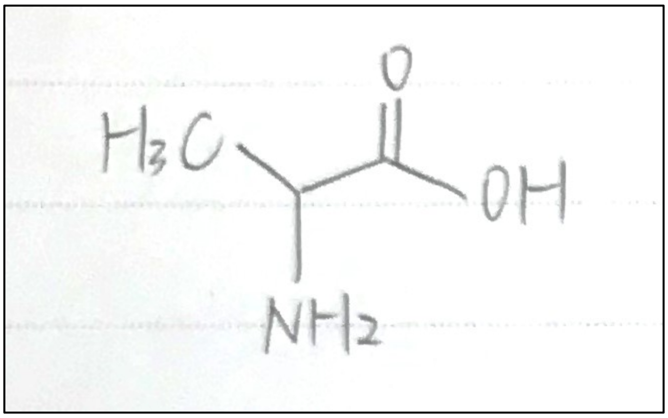

Figure 4: Skeletal formula for alanine

Instead, students typically use perspective drawings, with specialized symbols for bonds (dashes and wedges) to differentiate atoms which do not lie on the same axis/plane (Figure 5). Not only do perspective drawings capture the information of structural and skeletal formulas, but they are also able to depict the rough angles between atoms, and the geometry of the molecule in space.

However, perspective drawings are still two-dimensional theoretical representations of the three-dimensional molecule, where the angles are merely indicated. Therefore, a more accurate depiction of molecules in space would be the ball-and-stick diagram, where the individual atom is drawn as a sphere and the bonds between them, rods (Figure 6). Wu and Shah (2004) remarked that these forms of molecular representations required spatial cognition, the ability to “recognis[e] graphic conventions, manipulate[e] spatial information provided by the molecular structure and mentally track constraints based on concepts.”

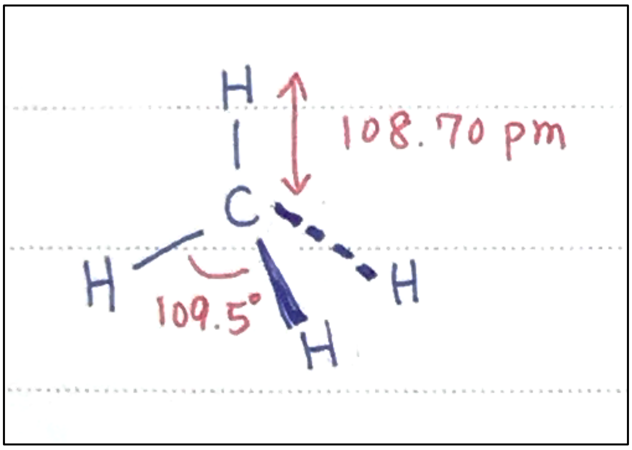

Figure 5: Perspective drawing of methane

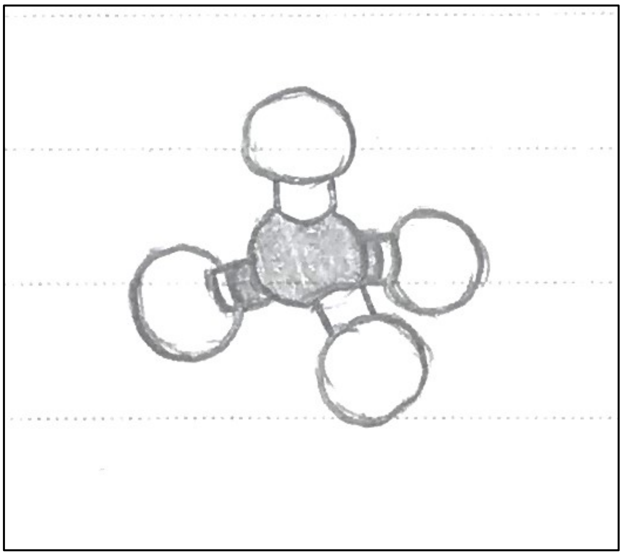

Figure 6: Ball-and-stick diagram of methane

3. Methodology

It was in an attempt to help learners in their spatial cognition that the study described in this paper was conceptualized and enacted. The study described in this paper was one of two parallel studies initiated by the present authorial team in the latter half of 2018. The smaller of the two parallel studies was enacted in a group of high school students in Singapore. The larger study – described in this paper – was enacted in an undergraduate curriculum in Taiwan.

Thirty-six third-year undergraduate students from the Department of Chemistry, National Pingtung University, participated in the intervention involving the use of Google's Augmented Reality application *Just a Line*. The students were drawn from two different courses, namely Advanced Biochemistry and Fundamentals of Microbiology, and about sixty percent of them reported they had not experienced Augmented Reality or related software, prior to the intervention. All students had studied General Chemistry and General Biology at earlier stages of their formal education.

The intervention was carried out over two weeks in September 2018. The schedule of implementation was as follows:

First week:

1. Review the VSEPR theory.
2. Ask students to check if their cell phone supports Augmented Reality.
3. Ask students to draw the NH_3 molecule by the app (*Just a Line*), making sure they capture the different angles and rotations of their molecule with the app's built-in screen-recording function.

Second week:

1. Review the VSEPR theory.
2. Ask students to draw the NH_3 molecule on paper.
3. Ask students to draw the glucose molecule on paper.
4. Ask students to draw the glucose molecule by app (*Just a Line*) as homework.
5. Introduce the concept of optical isomerism.

6. Ask students to draw on paper any pair of optical isomers.
7. Ask students to draw the amino acid molecule by app (*Just a Line*) as homework, rotating to observe their sketch from the opposite perspective.

After using the Augmented Reality app, students were instructed to draw the three-dimensional representations of the molecules again as a paper-based assessment. Interviews were also conducted with students to gather opinions about the effectiveness and ease-of-use of the Augmented Reality app. Raw data were collected in the form of scans of the students' paper-based drawings, videos of the three-dimensional sketches in Augmented Reality, and interview transcripts.

For this intervention, perspective drawings and ball-and-stick diagram were considered the most appropriate at representing the understanding of the VSEPR theory. Students were familiar with the model, as actual ball-and-stick models (constructed out of wood or plastic) were often used to aid classroom teaching of basic stereochemistry.

4. Results

Making use of the Augmented Reality app *Just a Line*, students were instructed to draw the entire model (the structural formula) in a three-dimensional format. As they gave form (reified) their sketches, they would have to walk around it in order to draw the atoms and bonds on different planes. These three-dimensional sketches would be recorded from within the app itself, in real time, as they were being sketched.

The thirty-six participants made a total of 80 three-dimensional sketches . The resulting videos of the students' three-dimensional sketches were coded (Table 1):

1 = drawing structural or skeletal formula (no evidence of three-dimensionality of a molecule.)
2 = three-dimensional structure of central atom present, but side groups (e.g., $-CH_4$, $-NH_2$ and -COOH) incomplete.
3 = molecule shape present, inaccurate bond angles (the idea of atoms on different axes not accurately grasped.)
4 = accurate three-dimensional visualization of a molecule.

Table 1: Summary of sketches in three-dimensions

	NH_3	CH_4	Glucose	Amino acid
1	1	1	0	2
2	0	0	0	10
3	2	7	0	2
4	24	19	3	9

These 80 three-dimensional sketches were compared with participants' pen and paper sketches before the intervention, as well as with similar paper-based sketches after the intervention.

The post-intervention paper-based sketches were coded (Table 2):

1= structural displayed or skeletal formula.
2 = perspective drawing.

3 = attempt at a ball-and-stick diagram, but an inaccurate depiction of depth (appears flat/on a single plane.)
4 = ball-and-stick diagram.

Table 2: Summary of sketches on paper

	NH_3	CH_4	Glucose	Amino acid
1	0	0	0	1
2	3	3	2	2
3	0	2	2	5
4	27	25	25	23

Space constraints permit only an in-depth analysis of three of these three-dimensional sketches, and this is reported in the section which follows.

Following the sketching and drawing, students were also asked their views towards the effectiveness of the app in teaching the VSEPR and optical isomerism concepts.

Attitudes towards sketching representations of molecules on the app were mostly positive. Students expressly stated in their answers that their experience with the app was positive, coded with comments such as "感覺很好"(very good), "很有趣" (very interesting), "還不錯 "(not bad) and "感覺很特別" (very special/extraordinary).

In response to the questions "what are your feelings towards using the Augmented Reality app as a learning tool for stereochemistry? How different is it from drawing stereo images on flat paper?", students reported that the app was superior at depicting the position of each atom in space without the constraints of flat paper, which could only show the x- and y-axes.

However, seventeen students also commented that using the app to draw the molecules was much more challenging and "很費功夫" (very effortful). Some reasons that were stated were that an understanding of three-dimensional space and depth was necessary to align the drawing in space and use the app effectively. Typical comments included:

> "Very special experience, compared to 2D drawing, when drawing the structure with Augmented Reality program, we must consider the problem of distance (depth of field), so I feel that it is more ambiguous to draw, but it is relatively simple in understanding, and can be looked at from 360 degrees."

> "This is the first time I have used this method. It feels very interesting, and it is harder to look at than it looks. It is difficult to align. It is often seen from this point of view, but from another perspective it took a lot of effort to draw, but it's clearer that it's a three-dimensional structure than with flat paper."

> "Compared to the structure of the textbook, I feel that Augmented Reality can give me a clearer understanding of the concept of structural linkage forward and backward."

> "The Augmented Reality app is a kind of strong augmented reality. It can see the 3D stereo structure at a glance. Because the three-dimensional structure of the flat paper is often foggy and difficult to

imagine, it can only be seen from the x-, y-axis. Structure, but after using this app, the stereo structure will really be clear at a glance."

"This way of using Augmented Reality is very novel. Although it takes a lot of time to draw on the picture, it does feel the feeling of a three-dimensional structure. Although the graphic of flat paper is easier to draw, if you want to see the three-dimensional structure, you really need a little imagination, otherwise it will be very painful, especially when it is really difficult to observe the mirror isomers. Painting can be seen."

"I feel that it feels good and using the Augmented Reality app allows me to look at the structure from multiple angles. I can understand the three-dimensional structure of the compound better than the flat paper drawing."

"I feel very fresh and feel very good. Flat paper is much less sophisticated than drawing a stereo image, and it is necessary to pay attention to the front and back distance when drawing a stereo image."

"I feel more aware of the actual molecular structure than the paperwork, which makes the molecule more impressive."

"Although the three-dimensional structure of the whole molecule can be clearly understood by the Augmented Reality app, the flat paper cannot be used, but the operation is not easy to draw the imagination image in the brain, and the sense of space is quite difficult."

Another set of questions posed to the participants was "after learning the stereo image of the compound using the Augmented Reality app, are you more aware of the stereo configuration of the compound in space? Was it easier to understand the effect of VSEPR theory on the structure and chemical properties of compounds? And are you more confident in distinguishing the structure of L-form and D-form amino acids?"

Thirty-two students reported that the app enhanced their understanding of the three-dimensional molecular structure and VSEPR theory. A similar number also reported that the app helped them to distinguish optical isomers, L-form and D-form, better as well. The following is a typical comment:

"Yes, it is possible to suggest that the front-back direction of the bond is known, and the repulsion between the forces at the time of forming the bond causes a structural change. In terms of resolution, it is also known that the front and rear directions of the entire bond are different."

A final question posed was "after learning about the stereo image of the compound with the Augmented Reality app, do you think it is an effective tool for learning?" Typical comments included:

"This program is very practical for me. This is the first time I have used the Augmented Reality system to learn the chemical structure. This is very interesting and looks simple. But I personally tried to find that it is very difficult to control the painting. But this can be actually understand the structure of the structure, you can even see the structure from the back."

"Augmented Reality app does allow me to understand the structure of the molecule better, although I have encountered many problems in the process of painting. For example, if the distance is not grasped, the molecular structure will run away, and the angle will not be correct. Blame, these puzzles make it almost take me ten minutes to draw a structure, but this app really makes me more tangible obstacles in the atoms of the molecule, and makes it easier for me to see the three-dimensional structure and judge the mirror isomers. These are the effects that are difficult to achieve with flat paper. This app is indeed a good learning software."

"I think the effective learning tool. Because I am very obsessed with stereoscopic things, but through the Augmented Reality app program, the program can understand the angle, distance and other things that the plane can't display. After use, I feel that the stereoscopic drawing or the stereo configuration is not. It feels really good."

5. Analysis

Recall that in the preceding section, it was described that the videos of the students' three-dimensional sketches were coded as follows:

1 = drawing structural or skeletal formula (no evidence of three-dimensionality of a molecule.)
2 = three-dimensional structure around the central atom present, but side groups (e.g., $-CH_4$, $-NH_2$ and -COOH) not fully drawn to show the three-dimensional structure.
3 = molecule shape present, inaccurate bond angles (the idea of atoms on different axes not accurately grasped.)
4 = accurate three-dimensional visualization of a molecule.

We report here on an example each of a video coded '2', '3', and '4', respectively.

The incidence of '2' occurring was more prevalent in the videos for amino acid isomers when atoms on individual chemical groups (e.g., $-NH_2$ and ethyl $-CH_3$) were drawn on incorrect planes, while the central atoms contained three-dimensional features. This could suggest that visualizing three-dimensionality of molecules is more difficult if there are more than one central atom.

Figure 7 below is an example of a three-dimensional sketch being coded as '2' (three-dimensional structure around the central atom (C – carbon atom) is present, but the side groups (COOH, NH_3, and CH_3) not fully drawn to show the three-dimensional structure.)

Figure 7: Three-dimensional sketch of molecule with side-groups not fully drawn.

For this student, we can see that the three-dimensional shape of the molecule is accurate, which each side group has drawn on a different axis. However, the side groups themselves are written in their empirical formula instead of its full structural form. This drawing is hence incomplete as one cannot see all its three-dimensional features.

As an example of a three-dimensional sketch coded as '3' (molecule shape present, inaccurate bond angles), consider the following series of five related figures (Figures 8 to 12), depicting a single attempt at sketching in three-dimensions as the learner rotates his/her body around the molecular representation being incrementally reified.

Figure 8: Three-dimensional sketch of molecule with inaccurate bond angles.

Figure 9: Three-dimensional sketch of molecule with inaccurate bond angles.

Figure 10: Three-dimensional sketch of molecule with inaccurate bond angles.

Figure 11: Three-dimensional sketch of molecule with inaccurate bond angles.

Figure 12: Three-dimensional sketch of molecule with inaccurate bond angles.

In this case, it is clear that the student is drawing the C and three H atoms from the same view, before turning and drawing the last H. This results in the situation where the three H atoms are on the same plane, meaning they are wider around the C atom rather than the 109 degrees of a tetrahedral shape that CH_4 is, and thus, contains incorrect angles. The accurate way to draw a tetrahedral in the Augmented Reality app would have been to draw the C in the center with a single H atom bonded above it; then, to rotate around the sketch, drawing each of the three bottom H atoms from different views.

What is particularly significant in the case of this student is that he/she was able to sketch the molecule correctly, when asked to do so on paper. These attempts are shown in Figures 13 and 14 below.

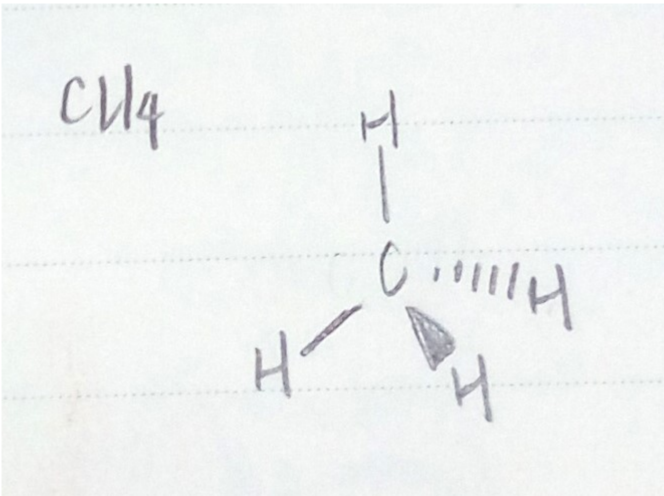

Figure 13: Perspective drawing on paper by same student.

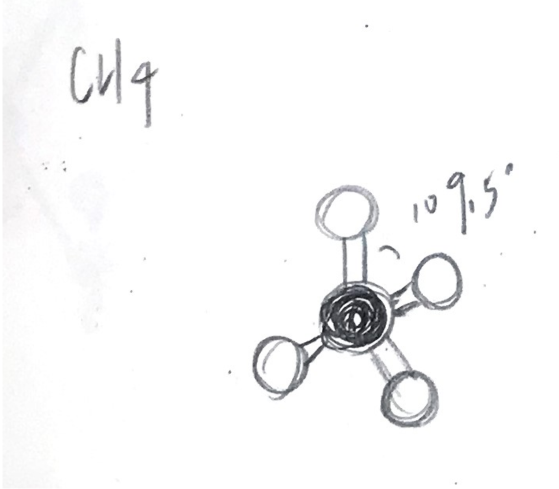

Figure 14: Ball-and-stick drawing on paper by same student.

Finally, the following series of three related figures (Figures 15 to 17) present an example of a sketch coded '4' (accurate three-dimensional visualization of a molecule). In this particular case, the molecule was alanine.

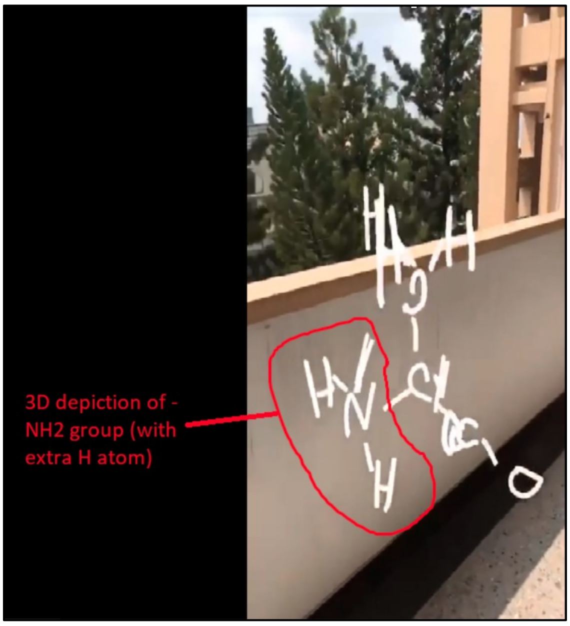

Figure 15: Accurate three-dimensional sketch of molecule.

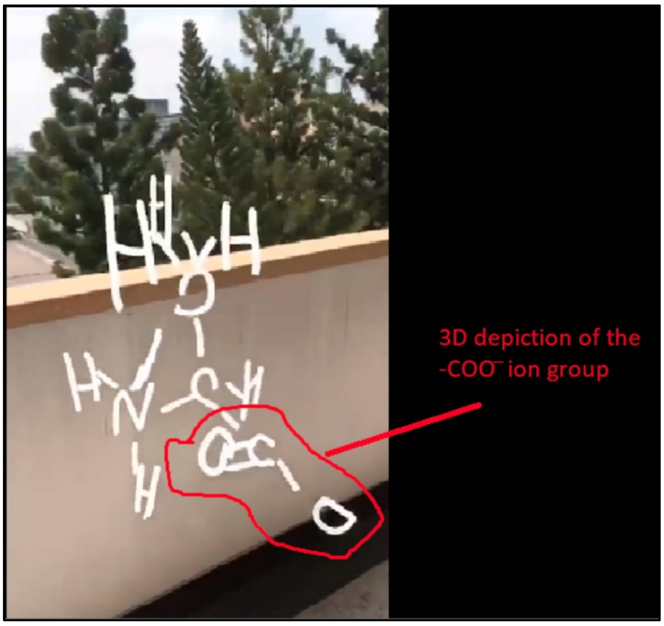

Figure 16: Accurate three-dimensional sketch of molecule.

Figure 17: Accurate three-dimensional sketch of molecule

From each angle, one sees a clear three-dimensional depiction of each side-group, suggesting that they are drawn on different axes.

6. Discussion

The preceding analysis has described how the approach of Learner-Generated Augmentation was used in a college-level chemistry course, to help surface conceptual difficulties among students, which would otherwise have gone undetected.

From the perspective of Disciplinary Intuitions (Lim, 2015), because much of chemistry operates at the atomic and sub-atomic levels, various concepts of chemistry can be difficult to grasp. This is especially prevalent when dealing with three-dimensional models. Even though there are notations to represent objects pointing into the plane and pointing outside of the plane, thereby assisting in the transposition of a three-dimensional model on to the planar surface of a sheet of paper, many students still find it difficult to visualize the model. This problem can be tackled with the use of Augmented Reality in learning. The concepts of Valence Shell Electron Pair Repulsion (VSEPR) theory, giant molecular lattice structure, hybridization of carbon atoms will be used for exemplification.

Using VSEPR theory, the shape and the bond angles of a molecule can be deduced. However, it is difficult to conceptualize the various VSEPR theories and some students are unable to visualize the diagram and hence, often get confused with the various bond angles, bond pairs, lone pairs, and shape.

Giant molecular lattices are also known as network covalent solids. They do not consist of separate or discrete molecules. Instead, the atoms in the compounds are held together by covalent bonds that extend in three dimensions throughout the sample. For example, in diamond, each carbon atom is tetrahedrally bonded to four other carbon atoms, an arrangement that extends throughout the lattice. However, due to the complex structure and the three-dimensional shape, some students are unable to visualize it which makes it extremely difficult for them to draw that structure.

In hybridization theory, atomic orbitals mix to form new orbitals called hybrid orbitals. However, some students might not be able to visualize the relative position of the various orbitals, and the drawing of hybridized orbitals often gets messy resulting in the students getting confused by their own drawing.

The approach of Learner-Generated Augmentation addresses many of these issues by providing teachers and curriculum designers with a means through which to gain insights into novice conceptions that might otherwise remain tacit (because the novices might still be able to sketch the molecules in terms of formal codifications).

It also helps learners appropriate the epistemic frame (Shaffer, 2007) of the domain expert, and connect book knowledge to everyday phenomena, as reflected in the following comment from a participant in the study:

"It's completely, I feel like I'm entering the world of science fiction, because I don't feel very good about stereochemistry. I often listen to the teacher explaining that this key is toward us and away from us, but I believe that everyone's imagined structure will be different if the molecule is more complicated, it is completely difficult to imagine what the structure looks like, so the understanding of this kind is a little inadequate. Now with the Augmented Reality app software, every time I see the three-dimensional structure, I want to try to draw, no matter where I am. It can be used anywhere, but I hope that this Augmented Reality App software is not limited to mobile phones above iPhone 6, so that everyone can use it to help learn."

Rising above to a more general level of abstraction, we would like to propose the following tips as guides for thinking about applying the approach of Learner-Generated Augmentation to other cases of learning, beyond molecular structures. The present authors readily acknowledge that Learner-Generated Augmentation is not a universal solution to problems of representation and visualization in learning. It is but one arrow in the teacher's quiver of tools and pedagogical approaches.

Having said that, we believe it is particularly appropriate when the concept in question has inherent dimensionality – if not, more traditional media of representations (such as pen and paper, and/or tablets) are just as well used.

Likewise, Learner-Generated Augmentation lends itself particularly well when there is an authentic reason for annotations from the learners themselves – if not, the curriculum designer might well choose to use media such as video, in which the annotations are more professionally rendered.

In sum, we encourage our fellow educators to ask themselves the question "what is difficult to see, but one knows intuitively is happening/taking place?"

One's responses to this – in the context of one's respective disciplinary domain – will help guide suitable use cases for the application of Learner-Generated Augmentation.

7. Conclusion

This paper has sought to describe a pedagogical approach which the present authors term Learner-Generated Augmentation.

The technology described in this paper is still nascent and is generally supported by smartphones made from 2016 onwards. The Augmented Reality space on handhelds is one that is rapidly evolving and what is state-of-the-art now will no longer be thus given the passage of months, not years.

Almost all major technology companies are in the midst of concerted pushes in to developing Augmented Reality for the general public. Apple is no exception. At the time of writing, one of the blurbs on its website read:

"First-hand experience is one of the most powerful ways to learn. And with augmented reality, you can experience just about anything you can imagine. Break down the complicated mechanics of a car engine before touching a spanner. Or analyse the most minute bones of the human body without making a single incision. The possibilities for learning are endless."

These statements are factually true and cannot be disputed.

What this paper has attempted to do is to encourage teachers, school leaders, and curriculum designers to approach the question of Augmented Reality in education from a diametrically opposed, yet complementary, perspective.

That perspective is best described in reversing the sequence of words in Apple's blurb, such that it reads: "First-hand experience is one of the most powerful ways to learn. And with augmented reality, you can *imagine* just about anything you can *experience*."

As one of the participants in the study expressed:

> "Augmented Reality app 可以提升學生學習化合物立體結構的点趣，可更直觀了解化合物在空間中的組成。"
>
> ("Augmented Reality app can enhance students' interest in learning the three-dimensional structure of compounds, and can more *intuitively* understand the composition of compounds in space.") [emphasis authors']

Harking back to Husserl's (1913) 'objects of the mind' and notions of proper and improper presenting, several students also mentioned that being able to draw using the app helped to express their idea of the shape of the molecule that previously would only have existed in their imagination. The following comment is an example:

> "畫起來感覺比較難畫，因為多了立體空間的概念，可是用 AR App 比較能了解整個原子的立體模型，不像平面只能利用想像的方式大概知道結構"

("It feels more difficult to draw because of the concept of three-dimensional space. However, the Augmented Reality app can compare the three-dimensional model of the whole atom. Unlike drawing on flat paper, where you can only know the structure by way of imagination.")

The approach of Learner-Generated Augmentation is thus deeply phenomenological in orientation, and – in the opinion of the authors – affords teachers and curriculum designers hitherto untapped ways of surfacing the intuitions and conceptions of learners that were once tacit.

This is because the curriculum design paradigm of Learner-Generated Augmentation is to place responsibility for creation of Augmented Reality artifacts in the hands of the novices (as opposed to the technology providers), using regular equipment from their own pockets, in such ways that the augmentations are canvases expressing the development of their own naïve and evolving understanding of curricular concepts.

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Appendix: System/hardware requirements

Android

ARCore requires:

Android 7.0 or later
Device that originally shipped with the Google Play Store

iOS

ARCore requires an ARKit compatible device running iOS 11.0 or later.

The following iOS devices are supported:

Any iPhone released after September 2015, including iPhone SE, 6S and 6S Plus
Any iPad released after March 2017
Any iPad Pro