



RESEARCH ARTICLE

REVISED Integrating augmented reality technology in education: vector personal computer augmented reality [version 2; peer review: 2 approved, 1 approved with reservations]

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Abstract

Background: Educators often face difficulties in explaining abstract concepts such as vectors. During the ongoing coronavirus disease 2019 (COVID-19) pandemic, fully online classes have also caused additional challenges to using conventional teaching methods. To explain a vector concept of more than 2 dimensions, visualization becomes a problem. Although Microsoft PowerPoint can integrate animation, the illustration is still in 2-dimensions. Augmented reality (AR) technology is recommended to aid educators and students in teaching-learning vectors, namely via a vector personal computer augmented reality system (VPCAR), to fulfil the demand for tools to support the learning and teaching of vectors.






Methods: A PC learning module for vectors was developed in a 3-dimensional coordinate system by using AR technology. Purposive sampling was applied to get feedback from educators and students in Malaysia through an online survey. The supportiveness of using VPCAR based on six items (attractiveness, easiness, visualization, conceptual understanding, inspiration and helpfulness) was recorded on 5-points Likert-type scales. Findings are presented descriptively and graphically.



Results: Surprisingly, both students and educators adapted to the new technology easily and provided significant positive feedback that showed a left-skewed and J-shaped distribution for each measurement item, respectively. The distributions were proven significantly different among the students and educators, where supportive level result of educators was higher than students. This study introduced a PC learning module other than mobile apps as students mostly use laptops to attend online class and educators also engage other IT tools in their teaching.

Conclusions: Based on these findings, VPCAR provides a good prospect in supporting educators and students during their online

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Any reports and responses or comments on the article can be found at the end of the article.

teaching-learning process. However, the findings may not be generalizable to all students and educators in Malaysia as purposive sampling was applied. Further studies may focus on government-funded schools using the newly developed VPCAR system, which is the novelty of this study.

Keywords

Augmented Reality, Teaching and Learning, Learning Vectors, Online Class



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REVISED Amendments from Version 1

This version is mainly addressing the reviewers' comments, especially on how the AR learning module works and on the elaboration of the developed system, VPCAR. The gap of this study is being highlighted by comparing to current literature review. We also provided more supporting literature by citing the related studies. In addition, clarification is done on how the objective IV of the study can be met by obtaining qualitative feedback using measurement of Likert scale.

Any further responses from the reviewers can be found at the end of the article

Introduction

In the 21st century, the education system is slowly moving towards digital learning or online learning by integrating web 2.0¹ and other technology tools in the teaching-learning process. Blended learning activities are integrated in the courses especially in higher education in Malaysia. These e-learning systems would encourage learners to learn at anytime and anywhere. Several courses related to blended learning such as flipped classroom,² massive open online courses (MOOCs)³ are being conducted to upskill educators and support them by providing the facilities and devices. However, secondary and primary schools in Malaysia are still focusing on physical classes. Lately, the lockdown of the country due to the coronavirus disease 2019 (COVID-19) pandemic has caused all school, colleges and universities to conduct fully online classes in order to ensure that teaching-learning can take place without physical classes.

The emergence of technology is gradually changing the pedagogy of teaching-learning especially for mathematics subjects. Before such technology, educators wrote the equations on a black board to show the steps of the solution. This was followed by the use of portable overhead projectors. Up to now, educators have often used liquid crystal display (LCD) projectors to present Microsoft PowerPoint slides of the subject content. With the multimedia tools integrated with PowerPoint, it is much easier to stimulate students' understanding on mathematics subject than using black/white board.⁴ However, educators always feel challenged to illustrate the presentation of vectors and planes to students by using the traditional way such as white board or PowerPoint slide, especially when involving more than 2 dimensions.⁵

In this study, augmented reality (AR) technology is introduced to support educators in their teaching-learning process especially when classes are conducted fully online. It can add an extra element of interaction, where user can treat it as if there is an actual object in front of them through visual-motor interaction compared to other online interactive tools. Some AR systems need special device such as head mounted device or pinch gloves but most of systems are developed on the portable and stationary device such as tablet, smartphones and desktop PC depending on user conveniences.^{6,7} The use of AR technology leads to positive effect on improving the visual thinking of students⁸ and promoting excitement during the learning process. Hence, feedback was being gathered from educators and students regarding the AR interface, understanding through visualization and inspiration in learning in this paper.

Literature review

Augmented reality is one of the emerging technologies which bring great impact to different application domains.⁹⁻¹² Different types of tools have been created by merging virtual objects with the real world in a scenario-based application. The interaction of the technology creates fun and gains users' attention, such as AR mobile game Pokemon Go¹³ which was a successful proof of concept of AR in year 2016 and attracted many users' attention in the world especially the young people (predominantly 21-30 years old).¹⁴

It is crucial to let students understand fundamental concepts before applying the knowledge in problem solving. Any misconceptions could lead to incorrect decisions. Hence, educators try to use effective teaching-learning methods to make sure students really understand. Sometimes, it is challenging to explain abstract contents to students especially for science, technology, engineering and mathematics (STEM) subjects. Educators have tried using different AR tools over the past two decades.^{10-12,15} For example, in physics, the AR technology has been implemented in STEM education and showed positive effect in the process of teaching-learning abstract concepts such as forces, mass and other properties.¹⁶ Besides that, an education tool was developed by Matsutomo *et al.* to observe the movement of magnetic fields using real-time visualization system¹⁷ and Chen did a comparison between representation of AR and physical models in learning amino acids.¹⁸ Physical Education teachers have also revealed that AR is a great tool in improving human motion skill and preserving human health competence.¹⁹ The improvement of AR technology and pedagogical methodology may allow learners to absorb the knowledge faster.

Regarding mathematics related research, several studies have looked at geometry especially for 3-dimension models,²⁰ but limited research has focused on vectors. The visualization of 3D geometry is challenging for students because

it is hard for students to picture 3D spatial situation given only 2D figures.^{21,22} Construct3D was developed based on “Studierstube” in geometry education²³ and has been further applied in a PhysicsPlayground simulation.²⁴ Other 3D geometry AR tools which are developed on mobile phone such as Geo+²⁵ and Sketchup software²⁶ that enable students to view solid models by scanning the QR code acting as markers while ScholAR²⁷ was designed to be markerless to assist in learning lines and types of angle on a 3D model. GeoGebra²⁸ can display 3D objects that can be placed in a real environment such as on a floor or any other flat surfaces.

Like geometry, vectors are a common abstract property in mathematics, which consists of direction and magnitude. Vectors are typically represented in a directed line with an arrow. Its quantities include displacement, velocity, position, force, and torque which are used in STEM subjects. The marker-based system, cleARmaths²⁹ displayed the vectors and virtual plane in 3-dimensional vectors on a portable device. Angel and Anabel *et al.* used gestures and body movement with the help of Kinect device in learning Euclidean Vectors, where only a small area is needed.^{30,31} To improve 3D visualization through visual-motor manipulation, Vectors AR3-APP was developed to support the educators and students in teaching and learning three-dimensional abstract concepts such as vectors and linear algebra where the learning module was developed in mobile apps.³²

AR systems have been developed in mobile apps, desktop computers, tabletops and other devices. One study revealed that users prefer more the use of a desktop AR system than mobile system in that the desktop AR system gained significant positive feedback in terms of responsiveness of the AR application.³³ In order to have better quality illustration by using smartphones, the users may need a higher specification smartphone which is costly. Hence, a new desktop AR markerless based system, namely Vector PC AR system (VPCAR), developed in Python that can illustrate multiple virtual vectors, planes and normal vectors in a real environment, is proposed in this study to fill the gaps. This tool is recommended for face-to-face and fully online classes to aid educators and students in their teaching-learning process with the following objectives.

Objectives of this study:

- I. To attract the students' attention in learning vectors.
- II. To make it easier for the students in understanding vectors.
- III. To improve the students' visualization of the vectors' representation.
- IV. To strengthen the students' conceptual understanding of vectors through visualization.
- V. To inspire the students in learning vectors through its engagement and interactivity.
- VI. To help the students and educators in learning/teaching vectors during the COVID-19 pandemic.

Methods

AR learning module development

Initially, the vectors' learning module had been developed on a PC, where the vectors and plane were illustrated in a 3-dimensional coordinate system by using AR technology as illustrated in Figure 1. Python 3.6 and a laptop-integrated webcam are the main tools to develop the learning module with OpenGL3.1.5 and OpenCV4.1.0.25 library. The AR was

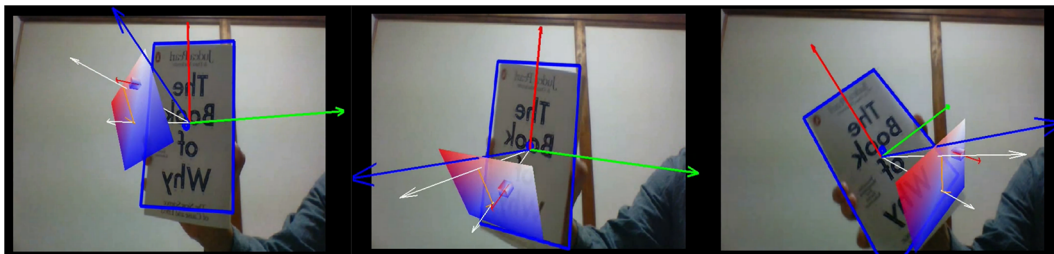


Figure 1. Illustration of vectors and plane by using Vector Personal Computer Augmented Reality.

PLANES

A plane in space is determined by a point $P_0 = (x_0, y_0, z_0)$ and a vector \mathbf{n} that orthogonal to the plane where \mathbf{n} is a normal vector.

Let $P(x, y, z)$, \mathbf{r}_0 and \mathbf{r} be the position vectors of P_0 and P .

\mathbf{n} is orthogonal to $\mathbf{r} - \mathbf{r}_0$.

$$\therefore \mathbf{n} \cdot (\mathbf{r} - \mathbf{r}_0) = 0$$

$$\mathbf{n} \cdot \mathbf{r} = \mathbf{n} \cdot \mathbf{r}_0$$

$$\mathbf{n} = \langle a, b, c \rangle \quad \mathbf{r} = \langle x, y, z \rangle \quad \mathbf{r}_0 = \langle x_0, y_0, z_0 \rangle$$

$$\therefore \text{Scalar Equation: } \langle a, b, c \rangle \cdot \langle x - x_0, y - y_0, z - z_0 \rangle = 0$$

$$a(x - x_0) + b(y - y_0) + c(z - z_0) = 0$$

is the scalar equation of plane through $P_0 = (x_0, y_0, z_0)$ with normal vector $\mathbf{n} = \langle a, b, c \rangle$.

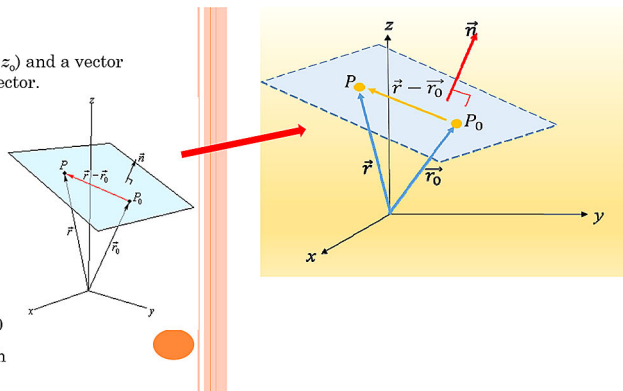


Figure 2. Illustration of vectors and plane by using Microsoft PowerPoint.

developed as a markerless AR system and a patterned flat surface is provided to extract the landmark features. Through homography, 3D perspective is inferred to generate the visualization.

The AR learning module is a program where the vectors can be initially set by the users. The AR vectors and planes were built so that they manifest themselves on patterned surfaces, like on top of a book. By moving the webcam, the users may view vectors from different perspectives. Currently, simple calculations can be performed. Position vectors and normal vectors on a plane can be presented in a 3-dimensional cartesian coordinate system by modifying the related vectors to be visualized in a file with scripts. Scripts is used instead of user interface as the user interface is under-developed. The output of this learning module was recorded as a short video demonstration and was attached in the questionnaire.³⁴

Questionnaire development

A questionnaire was designed based on the objectives of the study by using Google form to measure the supportiveness of incorporating AR technology in teaching and learning process during this pandemic.³⁵ It consisted of demographic information and the six measurement items based on the study objectives; attractiveness, easiness, visualization, conceptual understanding, inspiration and helpfulness. All items were measured by five-points Likert-type scale. The questionnaire was validated by an expert who has been teaching mathematics for more than 10 years and content validity was checked by using Pearson’s product moment test.³⁶ Cronbach’s alpha was used to measure the reliability of the questionnaire (discussed in the Results). A short video demonstration of vectors representation by using VPCAR and PowerPoint (duration: 2.12 minutes) was attached to the questionnaire.³⁴ Figures 1 and 2 are the screenshots. Ethics approval (EA1802021) was obtained from Multimedia University Malaysia, Technology Transfer Office (TTO). In addition, we obtained written informed consent from the respondents when completing the questionnaire.

Data collection

Primary data from 167 students and 71 educators in Malaysia was collected through email and social media invitation who are in our contacts such as Facebook, WhatsApp over four weeks from March to April 2021. A purposive sampling method was applied in the selection of target population of students and educators from secondary schools to universities in Malaysia because directly approaching the educators and students may provide more valid feedback.³⁷ However, the result may not be able to generalise due to purposive sampling was applied that causes possibility of bias concern and the sample size was referred to recent studies in the same domain.^{38,39} The questionnaire was sent via email. Descriptive results were presented graphically and in tabular format. Since the feedback was collected in ordinal form, therefore Mann-Whitney U Test and Chi-square test were applied. The analysis was done by using SPSS 26. Microsoft Excel may be used as open-access alternative.

Results

Demographic profile of students and educators

Table 1 shows the demographic profile of the 167 students and 71 educators who took part.⁴⁰ The majority of students were aged 18 to 25 years old (95%) and studying at diploma level (74.25%); the majority of educators were aged 31 to 40 years old (57.75%) and teaching higher education level (94.37%). Participants were mainly from private institutes (85.63%, students; 92.96%, educators). In total, 86.83% of students had learned about vectors before and 54.93% of educators taught vectors with an average teaching experience of 14 years.

During the COVID-19 pandemic, teaching-learning has been conducted fully online. Most students used a laptop or notebook (92.22%), followed by a smartphone (55.69%), represented in Figure 3. As shown in Figure 4, out of

Table 1. Frequency and percentage distributions of demographic profile of students and educators.

Characteristics	Students		Educators	
	n = 167	%	n = 71	%
Age (years)				
Under 18	3	1.80	-	-
18 ~ 25	160	95.81	-	-
26 ~ 30	3	1.80	2	2.82
31 ~ 40	1	0.60	41	57.75
41 ~ 50	-	-	24	33.80
51 ~ 60	-	-	4	5.63
Sex				
Female	41	24.55	51	71.83
Male	126	75.45	20	28.17
Studying/Teaching Institute				
Government	24	14.37	5	7.04
Private	143	85.63	66	92.96
Studying/Teaching Education Level				
Secondary School	2	1.20	4	5.63
Foundation/STPM	1	0.60	67	94.37
Diploma	124	74.25		
Degree	39	23.35		
Postgraduate	1	0.60		
Learn/Teach Vector				
Yes	145	86.83	39	54.93
No	22	13.17	32	45.07
Learning/Teaching experience				
Secondary School	115	68.86	Mean=14.07 Median=13 Mode=10	Max=30 Min=5 SD=5.17
Higher Education	30	17.96		
Not Applicable	22	13.17		

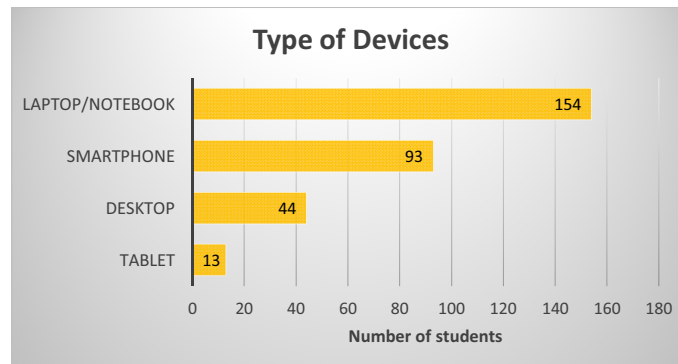


Figure 3. Type of devices used by students.

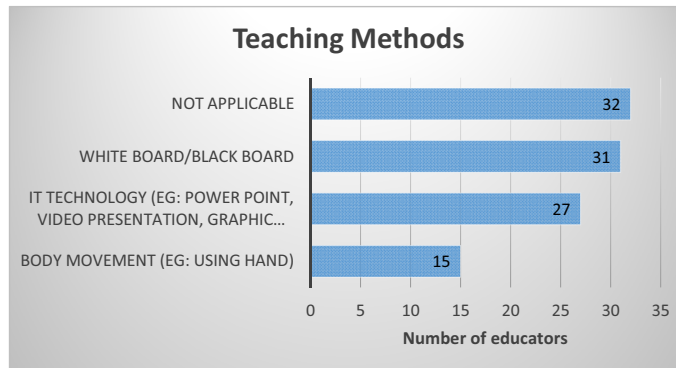


Figure 4. Teaching method used by educators.

39 educators, 79.49% of them used a white board or black board to teach vectors while 69.23% used IT technology such as PowerPoint, video presentation, and other graphic software. Less than 40% of them used body movement to teach vectors, where body movement refers to gestures, posture, head and hand movements or whole body movements.^{30,31} Especially for online classes, it is not easy to use body movement to present vectors via webcam. Hence, VPCAR could be of great help to them.

Several approaches can be used to measure the conceptual understanding of students such as qualitative and quantitative feedback.⁴¹ Educators commonly assess the students' understanding based on the correctness of answers. But it is challenging for educators to provide the quality feedback for each student during class especially for classrooms with large groups.⁴² Hence, this study obtained the quality feedback of educators and students' which provide measurement in Likert scale. It is crucial to obtain feedback from both parties to continue the suitable activities of teaching and learning in the class.⁴³

Figures 5 and 6 illustrate the feedback from the students and educators towards AR technology based on the six measurement items. Overall, the students and educators had provided a significant positive feedback towards incorporating AR technology in the teaching-learning process. From the diagram, the distribution of each measurement item among the students and educators are left skewed and J-shape respectively, which shows a significant difference in distribution at the 5% level of significance by using Mann-Whitney U Test. In Table 2, Cronbach's alpha of the six measurement items for students and educators are more than 0.9 which indicates an excellent internal consistency

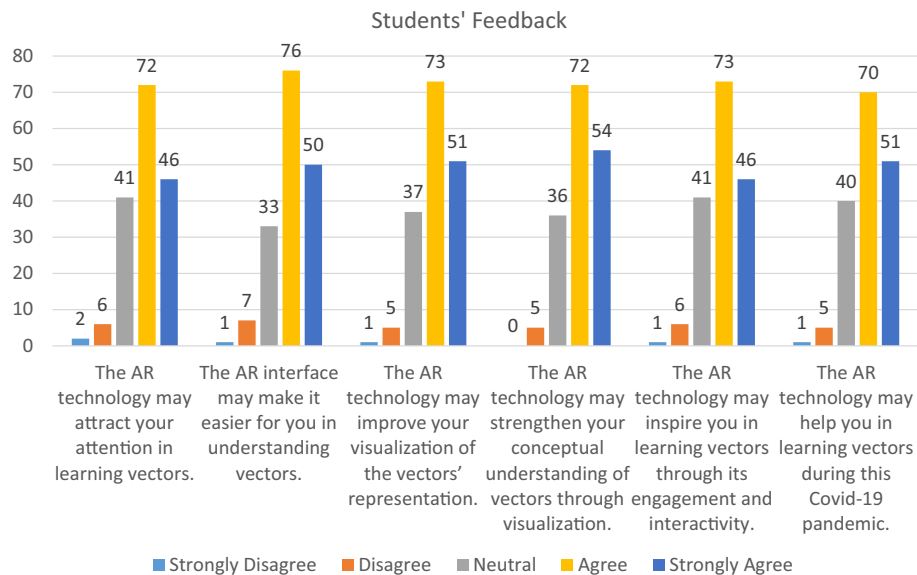


Figure 5. Feedback from students. AR = augmented reality; COVID-19 = coronavirus disease 2019.

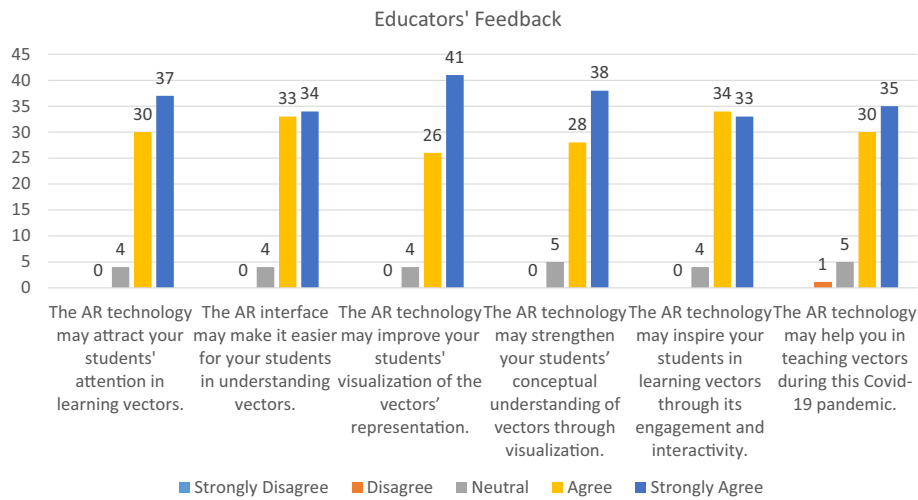


Figure 6. Feedback from educators. AR = augmented reality; COVID-19 = coronavirus disease 2019.

Table 2. Cronbach's alpha and Pearson product moment correlation coefficient, *r*. AR = augmented reality; COVID-19 = coronavirus disease 2019.

Measurement items	Students (Cronbach's Alpha = 0.944)		Educators (Cronbach's Alpha = 0.952)	
	<i>r</i>	<i>p</i> -value	<i>r</i>	<i>p</i> -value
The AR technology may attract your/your students' attention in learning vectors.	0.848	0.00	0.919	0.00
The AR interface may make it easier for you/your students in understanding vectors.	0.893	0.00	0.933	0.00
The AR technology may improve your/your students' visualization of the vectors' representation.	0.921	0.00	0.913	0.00
The AR technology may strengthen your/your students' conceptual understanding of vectors through visualization.	0.890	0.00	0.892	0.00
The AR technology may inspire you/your students in learning vectors through its engagement and interactivity.	0.889	0.00	0.877	0.00
The AR technology may help you in learning/teaching vectors during this COVID-19 pandemic.	0.863	0.00	0.869	0.00

in measuring the supportiveness on using AR technology in teaching-learning process. The content validity of the questionnaire was measured statistically by Pearson product moment correlation coefficient, *r*, which shows that all the measurement items is valid. In addition, the feedback was also measured by using mean score which is shown in Table 3. The mean score for each measurement item for educator category is higher than student category. This shows that the educators are more in support than the students in implementing AR technology tools in teaching-learning vectors.

Typically, educators teach by using Microsoft PowerPoint nowadays. Table 4 shows that more than half of students (67.07%) and educators (76.06%) were keener to use AR technology during teaching-learning process. The findings revealed that most students are using a laptop or notebook to attend online classes, therefore PC learning module is more preferred than mobile apps learning module. Nearly 80% of educators are keen to use PC AR tools. The positive association between learning/teaching method and learning module preferences was shown at 5% level of significance by using Chi-Square test with *p*-value = 0.021.

Discussion

In summary, the finding showed significant positive feedback towards the incorporation of AR technology in teaching and learning vectors from educators and students based on the six measurement items. The visual aesthetic of a system is

Table 3. Feedback of the six measurement items, measured on a 1-5 Likert-type scale. SD = standard deviation; AR = augmented reality; COVID-19 = coronavirus disease 2019.

Categories	Students		Educators	
	Mean	SD	Mean	SD
The AR technology may attract your/your students' attention in learning vectors.	3.92	0.88	4.46	0.61
The AR interface may make it easier for you/your students in understanding vectors.	4.00	0.85	4.42	0.60
The AR technology may improve your/your students' visualization of the vectors' representation.	4.01	0.84	4.52	0.61
The AR technology may strengthen your/your students' conceptual understanding of vectors through visualization.	4.05	0.81	4.46	0.63
The AR technology may inspire you/your students in learning vectors through its engagement and interactivity.	3.94	0.85	4.41	0.60
The AR technology may help you in learning/teaching vectors during this COVID-19 pandemic.	3.99	0.85	4.39	0.69

Table 4. Preferences of learning/teaching method and learning module.

Categories	Students		Educators	
	n = 167	%	n = 71	%
Preferences				
Learning/Teaching Method				
PowerPoint Slide	41	24.55	15	21.13
AR Technology	126	75.45	56	78.87
Learning Module				
Personal Computer	112	67.07	54	76.06
Mobile Apps	55	32.93	17	23.94

always the most important dimension in attracting the users' attention.⁴⁴ The effort of creating a colourful and animated interface could let students feel more interested and focused during learning as previous research has found that some students consider this dimension encouraging in continuing using their website.⁴⁵ Thus, colourful interface of AR could attract students' attention of various ages such as those in higher education, secondary school, primary school etc.^{46,47}

Furthermore, the main purpose of several augmented reality systems is targeting the improvement of the visualization of users^{17,18,23,24,30,32} as such it helps the users comprehend the fundamental concepts of particular content to avoid misunderstandings which was highlighted earlier in the literature review. AR tools are just an additional or supplementary method for explaining complex concepts which may be hard to be understood statically with our vision alone. Thus, the illustration of VPCAR make it easier for the students in understanding vectors through visualization as the students are able to view the vectors in different perspectives by moving their own PC's webcam. The students' visualization of vectors can therefore be improved compared to those who learn by using conventional teaching method. At the same time, AR may strengthen the students' conceptual understanding of vectors.⁴⁸

Learning can be divided into learner-centred or instructor-centred learning. It is important to engage and get feedbacks from students by using a mixed approach so that the students will not feel neglected. Educators always need to interact with the students so that the students will not lose their interest in learning. Through this engagement, students will be inspired and motivated in learning.⁴⁹ AR technology can increase the engagement of students as reported in a previous study.⁵⁰ Thus, VPCAR may be able to inspire the students in learning vectors through its engagement and interactivity as shown by results of this study.

The feedback of students and educators are useful in determining their readiness in adopting AR technology. AR technology is easy to customise with low preparation overheads (costs) and it supports animation. Nowadays, PCs have

become an essential electronic device in our lifestyle especially for working adults and students. VPCAR, which is developed for PC, requires less effort to use compared to other AR systems. As supported by the students and educators, VPCAR certainly provides great support to them in learning or teaching vectors during this COVID-19 pandemic.

Limitations

In this study, the findings may not represent all students and educators in Malaysia because a purposive sampling method was applied. Due to limited network connection, most respondents were from private institutes. For further study, government secondary school students shall be included to distinguish the usefulness of VPCAR perception at different educational institutes.

Conclusions

The outbreak of COVID-19 caused classes to be conducted fully online all over the world⁵¹ and several works studied the challenges and issues faced by the educators and students during the pandemic.⁵²⁻⁵⁴ In this study, VPCAR was applied to an online class domain that encounters the problems faced by educators and students in learning or teaching vectors. The positivity of survey responses based on the six measurement items: attractiveness, easiness, visualization, conceptual understanding, inspiration and helpfulness, with the range of means from 3.92 to 4.52 out of 5, indicates that VPCAR is able to achieve the objective of this study from the aspect of educators and students. In addition, at least 75% of the educators and students preferred to use AR technology compared to PowerPoint slides which indicates that both educators and students are ready in adopting the AR technology in teaching-learning process.

With the merit of AR technology, several challenges and issues still need to be addressed.^{55,56} The system provides visualization in real-time and requires internet connection. Hence, rural area students who lack of this facility may be unable to utilise this system efficiently. Increased internet access will give the opportunity to enhance this new technology. Furthermore, educators may also record the demonstration, so students are still able to learn it offline. The newly developed VPCAR system is the novelty in this study which is beneficial for the educators and students.

Data availability

Underlying data

Figshare: Integrating AR Technology in Teaching and Learning Vectors. <http://doi.org/10.6084/m9.figshare.14864853>.⁴⁰

Extended data

Figshare: VPCAR Questionnaire 2021. <http://doi.org/10.6084/m9.figshare.16608448>.³⁵

Figshare: VPCAR Video Demonstration 2021. <http://doi.org/10.6084/m9.figshare.16649029>.³⁴

Data are available under the terms of the [Creative Commons Zero “No rights reserved” data waiver](#) (CC0 1.0 Public domain dedication).

Author endorsement

Prof. Ts. Dr. Lau Siong Hoe confirms that the author has an appropriate level of expertise to conduct this research, and confirms that the submission is of an acceptable scientific standard. Prof. Ts. Dr. Lau Siong Hoe declares they have no competing interests. Affiliation: Faculty of Information Science and Technology, Multimedia University, Jalan Ayer Keroh Lama, 75450 Bukit Beruang, Melaka, Malaysia.

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Nur Idawati Md Enzai 

Universiti Teknologi MARA, Shah Alam, Selangor, Malaysia

This paper presents the implementation of AR to visualize vectors in education. Feedback from the users is also obtained and analyzed. I have a similar work implementing AR for computer hardware subjects but not as advanced as this work. This work utilizes Python and OpenGL. Therefore, I find the topic very interesting and look forward to future works to be executed. However, I hope the method of developing AR can be elaborated more, maybe it can be visualized in the form of flow chart, if possible.

Is the work clearly and accurately presented and does it cite the current literature?

Yes

Is the study design appropriate and is the work technically sound?

Yes

Are sufficient details of methods and analysis provided to allow replication by others?

Yes

If applicable, is the statistical analysis and its interpretation appropriate?

I cannot comment. A qualified statistician is required.

Are all the source data underlying the results available to ensure full reproducibility?

Yes

Are the conclusions drawn adequately supported by the results?

Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Computer Networking, Engineering Education

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Reviewer Report 22 March 2022

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Kenneth Y. T. Lim 

Office of Education Research, National Institute of Education, Singapore, Singapore

Thank you for investing time and effort in understanding the intent behind the suggestions from the earlier round of review.

I am satisfied that you have addressed them to the best of your ability.

Is the work clearly and accurately presented and does it cite the current literature?

Yes

Is the study design appropriate and is the work technically sound?

Yes

Are sufficient details of methods and analysis provided to allow replication by others?

Yes

If applicable, is the statistical analysis and its interpretation appropriate?

Yes

Are all the source data underlying the results available to ensure full reproducibility?

Yes

Are the conclusions drawn adequately supported by the results?

Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: AR in learning

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Author Response 23 Mar 2022

Sin Yin Tan

Thank you for taking the time and effort to review our manuscript.

Competing Interests: No competing interests were disclosed.

Version 1

Reviewer Report 09 December 2021

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**Deepti Prit Kaur**

Chitkara University Institute of Engineering and Technology, Chitkara University, Chandigarh, Punjab, India

In general, the research presented here is interesting. The authors have developed a mechanism for visualizing and understanding the concept of vectors in a 3D coordinate system through Augmented Reality. However, the paper lacks clarity in many places, which can be fixed with major revisions.

1. The authors are encouraged to explain why augmented reality technology is needed for understanding these concepts when some online interactive simulators are already available for the same purpose.
2. There are many applications existing for the use of AR in geometry. Authors could include more literature with respect to existing applications. Also, a research gap may be highlighted with respect to the reviewed literature.
3. The contribution in technical development is not clear. The only specifications given are "Python 3.6 and a laptop-integrated webcam are the main tools to develop the learning module with OpenGL3.1.5 and OpenCV4.1.0.25 library." In the methods section. It is not mentioned whether the system uses marker-based or marker-less AR. What can (or can't) be done with this application? Were any usability principles considered for application design?
4. It is not clear whether there is any way to perform the calculations on vectors using the developed application. How are the inputs given/how are the coordinates shown? These must be specified.
5. Some language corrections are needed. Also, at one place (in discussion section), VPACAR is written in place of VPCAR.

6. This research mainly focuses on the feedback of educators and students (as evident from Figures 5-6, and Tables 2-4) on the use of application with respect to six measurement items and user's preferences of learning/teaching methods. The efficacy of application in student's conceptual understanding must be found to meet objective IV of the study.

Is the work clearly and accurately presented and does it cite the current literature?

Yes

Is the study design appropriate and is the work technically sound?

Partly

Are sufficient details of methods and analysis provided to allow replication by others?

Partly

If applicable, is the statistical analysis and its interpretation appropriate?

I cannot comment. A qualified statistician is required.

Are all the source data underlying the results available to ensure full reproducibility?

Yes

Are the conclusions drawn adequately supported by the results?

Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Augmented Reality, Engineering Education Research

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 15 Mar 2022

Sin Yin Tan

Thank you so much for your valuable comments.

To address the comments that you had highlighted:

1. The AR concept is explained as such "AR can add an extra element of interaction, where user can treat it as if there is an actual object in front of them through visual-motor interaction". We added more explanation in the 'Introduction', the third paragraph in the paper.
2. Literature review had been extended in the third and fourth paragraph. The research gap is highlighted in the fifth paragraph, in the literature review.

3. We are using marker-less AR. Given a patterned flat surface, landmark features are extracted. Through homography, 3D perspective is inferred to generate the visualization. We added details in the 'Methods', in the 'AR learning module development'.
4. Currently, simple calculations can be performed. Position vectors and normal vectors on a plane can be presented in a 3-dimensional cartesian coordinate system by modifying the related vectors to be visualized in a file with scripts. Scripts is used instead of user interface as the user interface is under-developed. The output of this learning module was recorded as a short video demonstration.
5. We changed 'VPACAR' to 'VPCAR'.
6. To meet the objective IV of the study, several approaches can be used to measure the conceptual understanding of students such as qualitative and quantitative feedback. Educators commonly assess the students' understanding based on the correctness of answers. But it is challenging for educators to provide the quality feedback for each student during class especially for large group classroom. Hence, this study obtained the quality feedback of educators and students' which provides measurement in Likert scale. It is crucial to obtain feedback from both parties to continue the suitable activities of teaching and learning in the class.

Competing Interests: No competing interests were disclosed.

Reviewer Report 06 October 2021

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Kenneth Y. T. Lim

Office of Education Research, National Institute of Education, Singapore, Singapore

I appreciate the opportunity to review your manuscript, and have the following suggestions for your consideration:

- The manuscript is clearly structured in an orthodox manner. To refine its intelligibility, I draw your attention to minor conjunctive phrases which are inappropriately used. For example, in the Literature Review, the second paragraph, the fifth sentence begins with 'Therefore'. The use of 'therefore' is not appropriate unless you first establish a connection between the use of AR tools and how they might address challenges in the explanation of abstract concepts. In the same paragraph, you use 'Nevertheless'. again, this word is inappropriate because all the cited works in this paragraph point towards positive

outcomes, and therefore using 'nevertheless' makes little sense.

- In the third paragraph of the Literature Review, you say that the visualisation of 3D geometry is "somehow challenging". To your credit, you offer relevant cited works. Do please expand on them (at least briefly) because it is not appropriate in an academic paper to use 'somehow', when cited works can be elaborated upon to (at least partially) account for the 'somehow'. In the same paragraph, I do not understand your use of "to increase the mobility of users". I suspect it might be to do with the learning module in the mobile app, but this needs to be clearly explained. I also believe the word "whereas" in the last sentence of this paragraph is wrongly used, or - if it is correctly used - then the contrast (implicit in 'whereas') must be (very) clearly articulated.
- In 'Methods': 'AR learning module development', I am not clear about how the "vectors can be set by the users in the learning module", when "the learning module" is a "short video demonstration".
- In 'Methods': 'questionnaire development', 'mathematic' should be 'mathematics'. In the same paragraph, "Figures 1 and 2 were" should be rendered in the present tense.
- In 'Results': 'demographic profile'. In the second paragraph, you introduce the role of what you term 'body language' in the teaching and learning of 3D concepts such as vectors. While I understand implicitly what you refer to, I would like to suggest that 'body movement' / 'embodied action' be more appropriate than 'body language' (which has quite a different meaning). Second, still on this topic, while I understand what you mean, please try to find at least one or two literature-supported studies about embodied action / bodily movement in the teaching / learning of 3D concepts (such as vectors). This would strengthen your argument, because currently there is no prior context for you to abruptly introduce 'body language' at this stage of your manuscript.
- Still in this section, in the fourth paragraph, please insert 'are' in "nearly 80% of educators are keen".
- In the first paragraph of 'Discussion', you refer to "the colourful interface of AR", with the definite article "the". the use of color in the UI of AR is not necessarily a given, so please do not use the definite article ("the"). color is a possible attribute of UI in AR.
- In the third paragraph of 'Discussion', please correct the informal contraction "won't" to "will not". This occurs twice in the paragraph. Please also correct "won't lost" to "will not lose".

Is the work clearly and accurately presented and does it cite the current literature?

Yes

Is the study design appropriate and is the work technically sound?

Yes

Are sufficient details of methods and analysis provided to allow replication by others?

Yes

If applicable, is the statistical analysis and its interpretation appropriate?

Yes

Are all the source data underlying the results available to ensure full reproducibility?

Yes

Are the conclusions drawn adequately supported by the results?

Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: AR in learning

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 15 Mar 2022

Sin Yin Tan

Thank you so much for your valuable comments.

To address the comments that you had highlighted:

- In the Literature Review, the second paragraph, the fifth sentence begins with 'Therefore' and 'Nevertheless', we will modify the English accordingly.
- In the third paragraph of the Literature Review, the challenges will be elaborated as such "it is hard for students to picture 3D spatial situation given only 2D figures." and related studies are cited. For the second point, the sentence will be improved as such:
 - To improve 3D visualization through visual-motor manipulation, Vectors AR3-APP was developed to support the educators and students in teaching and learning three-dimensional abstract concepts such as vectors and linear algebra where the learning module was developed in mobile apps.
- In 'Methods': 'AR learning module development', the AR learning module is a program where users will set the function of the vectors. The short video is merely a means to show the output for this paper. We have clarified it in the second paragraph.
- In 'Methods': 'questionnaire development', we changed 'mathematic' to 'mathematics' and "Figures 1 and 2 were" to "Figures 1 and 2 are"..
- In 'Results': 'demographic profile', we modified 'body language' to 'body movement' where body movements include gestures, posture, head and hand movements or whole body movements. Related studies are cited.

- In 'Results': in the fourth paragraph, we inserted 'are' in "nearly 80% of educators are keen".
- In the first paragraph of 'Discussion': we changed "the colourful interface of AR" to "colourful interface of AR".
- In the third paragraph of 'Discussion': we changed "won't" to "will not". and "won't lost" to "will not lose".

Competing Interests: No competing interests were disclosed.

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