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Science and engineering students' difficulties in understanding vector concepts

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Abstract

The study assesses science and engineering students' difficulties in understanding vector concepts. Test of understanding of vectors was administered to 101 university students who were completing their second introductory physics course. Rasch measurement software (Winsteps) was used to analyze the raw data. The concepts that the students found most difficult were identified; these included the graphical representation of a unit vector, the graphical addition and subtraction of vectors, and the interpretation of the dot and cross products, among others. On the other hand, some concepts were easier for students, such as the magnitude of a vector presented in unit-vector notation, and determination of the components of vectors. No significant differences in understanding of vector concepts could be attributed to gender; however, engineering students outperformed science students in understanding vector concepts. This study offers recommendations that physics instructors and researchers can use to improve the teaching of vector concepts.

Keywords: physics education, vectors, Rasch measurement, Jordan

INTRODUCTION

An understanding of vector concepts is necessary to comprehend and master the topics of introductory level physics, such as force, velocity and acceleration (Barniol & Zalava, 2014a; Latifa et al., 2021; Nguyen & Meltzer, 2003; Susac et al., 2018). Many physical concepts such as force, velocity, acceleration, and others are represented by a vector (Bollen et. al, 2017). In turn, the understanding of vector concepts may affect students' understanding of other concepts: Sirait and Oktavianty (2017) found a significant relationship between students' understanding of vector concepts and their understanding of force concepts. Understanding vector concepts and operations is necessary to develop a deep understanding of force as a vector (Flores-García et al., 2008).

However, several studies have indicated that many students lack a basic understanding of vector concepts and operations (e.g., Appova & Berezovski, 2013; Heckler & Scaife, 2015). Students face difficulties in understanding vector concepts (e.g., Nguyen & Meltzer, 2003), and freshman college students may lack a fundamental understanding of vector concepts and basic vector operations (Appova & Berezovski, 2013). Even after completing an introductory physics course, many college students were found to lack an understanding of the two-dimension vector addition in research by Nguyen and Meltzer (2003). Barniol and Zavala (2012) found that the majority of students were not able to correctly sketch the unit vector in the Cartesian plane, and they also had difficulties with negative scalar multiplication.

While validating 20-item test of understanding of vectors (TUV), Barniol and Zavala (2014b) identified the most common student errors, including using the cosine function of the angle when the angle is measured from y-axis to calculate x component of a vector, treating both x and y components of the unit vector as equal to one, adding two vectors to determine the vector difference between two vectors in 1D, misinterpreting the dot product, and miscalculating the cross product, among others. A list of the most frequent errors is reported in Barniol and Zavala (2014b). In addition, Susac et al. (2018) identified a list of difficult concepts: unit vector, cross product, subtraction of vectors, the dot product of vectors, and the directions of vectors; among these, the unit vector concept was the most difficult concept.

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Contribution to the literature

- Extends the literature on assessing university students' difficulties in understanding vector concepts internationally, as this study was conducted in Jordan in the Middle East.
- Provides recommendations based on research on the difficulties of dealing with graphical representations and interpreting the dot and cross products.
- Uses a validated instrument, TUV, in a different country and provides evidence that supports its validity.

Moreover, Bani-Salameh et al. (2020) reported a list of frequent vector misconceptions, such as problems calculating *x*-component of a vector, use of the tip-tip method when adding vectors and multiplying a vector with a negative scalar having no effect on its direction.

Sirait and Oktavianty (2017) found that students were unable to add two vectors when they were presented in two dimensions, and that most students were unable to perform vector subtraction correctly. Other researchers examined students' difficulties in using both the algebraic and graphical representation of vectors (Klein et al., 2021). Latifa et al. (2021) found that it was difficult for students to produce a correct graphical representation of vector multiplication. Bollen et al. (2017) described difficulties in interpreting and switching between the representations of the vector; students struggled with vector addition when moving between the algebraic and graphical representations. Furthermore, they could not determine the start and the end of field lines.

Barniol and Zavala (2014a) investigated the effects of contexts on the understanding of vector concepts. Adding contexts worked in different ways: adding the context of work concept helped students apply the dot product correctly but adding the context of velocity caused the students to incorrectly deal with velocities as scalars (Barniol & Zavala, 2014a). Other researchers found that students faced more difficulties when they tried to add vectors with contexts added (Flores-García et al., 2008).

Nguyen and Meltzer (2003) emphasized the need for additional instruction to improve teaching vector concepts. To improve the teaching of vector concepts and overcome students' difficulties in understanding them, researchers have introduced new pedagogical teaching interventions (e.g., Ahamad et al., 2021; Karnam et al., 2018; O'Brien & Sirokman, 2014; Ouko et al., 2015). Ouko et al. (2015) recommended implementing peer instruction when teaching vector concepts, as this has a positive impact on student achievement in vector concepts. Karnam et al. (2018) suggested implementing an interactive computational system, named touchy-feely vectors, to allow students to connect the algebraic and geometric representation of vectors and perform the addition of vectors in an interactive way. Klein et al. (2018) suggested implementing interactive puzzles to help students make connections between the graphical and the algebraic representations of vectors. Additionally, O'Brien and Sirokman (2014) suggested the use of interactive games to support traditional vector learning in a fun and creative environment.

Research in physics education at the university level in Jordan is still in its early stages, and there is a need to promote physics education and improve the teaching of physics in the country. While there many international research studies have investigated students' understanding of vector concepts, this has not been the case in Jordan. Exploring whether some factors such as gender and chosen major (i.e., science or engineering) influence students' understanding of vector concepts may be useful for physics educators and researchers in Jordan. Thus, the purpose of this exploratory study is to identify students' difficulties in understanding vector concepts. The specific research questions are:

1. What are the most difficult vector concepts for science and engineering students?
2. Are there any significant differences between students' level of understanding of vector concepts that could be attributed to the students' gender or their chosen major (science or engineering)?

The comparison between majors was limited to science and engineering as most of the participants belonged to faculty of science or faculty of engineering. Moreover, mastering vector concepts is necessary to understand many models in science and engineering in particular.

The current study makes a significant contribution to the literature by identifying and understanding university students' difficulties in understanding vector concepts. Moreover, the current study may provide useful recommendations for further research related to students' difficulties in understanding vector concepts and increase interest in physics education in Jordan.

METHODOLOGY

This study used a descriptive research design (Creswell, 2002). TUV was administered to a sample of 101 participants, and the collected data were subsequently analyzed using Winsteps and SPSS to address the research questions.

Instrument

This study adopted TUV (Barniol & Zavala, 2014b) as a research instrument. Based on a comprehensive literature review, Barniol and Zavala (2014b) developed TUV as a 20-item test covering a wide range of vector concepts, such as direction and magnitude, unit vector, addition and subtraction of vectors, the dot product and the cross product, among others. The test items were mapped to the targeted vector concepts. The content validity of TUV was checked by a panel of experts. The item difficulty and item discrimination indices for the majority of items were acceptable; the point-biserial coefficient for all items was within the acceptable range (r≥0.20). Kuder-Richardson reliability index for TUV was 0.78 (Barniol & Zavala, 2014b).

Other researchers used a Rasch model to analyze TUV, which provided extra evidence supporting the validity of TUV (Susac et al., 2018). The infit and outfit statistics of the test items fit well with the model, indicating that the questions are of good quality. The outputs of the Rasch analyses were also utilized to provide evidence supporting the construct validity of TUV.

In conclusion, both classical test theory and a Rasch model were used to validate TUV, and both provided evidence supporting validity of TUV. In the present study, TUV was used to collect data from participants.

Participants

TUV was administered to a convenience sample of 101 students who were about to complete the second introductory calculus-based physics course, PHYS 102, at a public university in Jordan. The physics courses at this university are taught in English, and physics tests are administered in English. The assigned textbook for the introductory physics courses is *physics for scientists and engineers* (Serway & Jewett, 2014). The participants belonged to three colleges: engineering (n=55), science (n=36), and information technology (n=8); two participants did not report their majors. The participants joined five different sections taught by four different instructors. The breakdown of gender and choice of major in this convenience sample might not exactly represent their breakdown in the wider population. As for the Rasch measurement, a sample of 100 is enough for obtaining stable item calibration within (±0.5) logit, and a sample of 50 is suitable for obtaining stable item calibrations within (±1.0) logit (Linacre, 1994).

Data Collection

Hard copies of TUV were administered at the end of the Fall 2022 semester. It took participants around 30 minutes on average to complete the test in their physics 102 class.

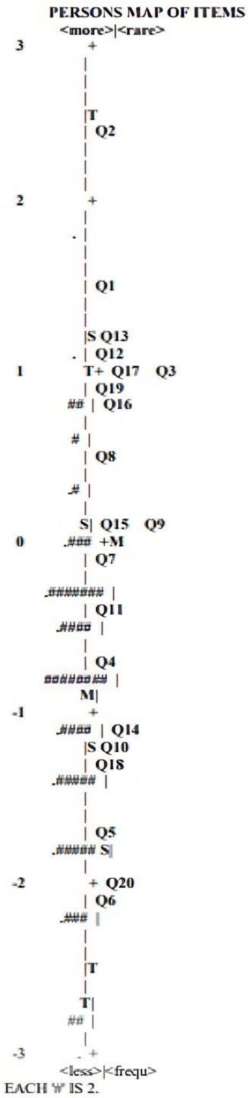

Figure 1. The item-person map (or Wright map) shows the participants' ability to understanding vector concepts against the questions' estimated difficulties (Source: Author's own elaboration)

DATA ANALYSIS AND RESULTS

A Rasch measurement model (Bond & Fox, 2015; Liu, 2010; Mohd Dzin & Lay, 2021) to analyze the collected data using Winsteps software (Linacre, 2006) and SPSS. The reliability indices, difficulty estimates of test questions, infit and outfit statistics, and PTMEA correlations were estimated using Winsteps software. Also, the item/person map (**Figure 1**) was produced.

Rasch analyses usually provide two reliability indices: item reliability and person reliability. The results show that the item separation and item reliability indices were 4.47 and 0.95, respectively, while the person separation and person reliability indices were 1.16 and 0.58 respectively. The item/person map (**Figure 1**) shows estimates of the difficulty of each test question against estimates of participants' abilities; both were estimated in logits. The map shows a good distribution

Table 1. Difficulty indices, infit, & outfit statistics, & point-measure correlations for test questions

No	Vector concepts covered by TUV questions, adopted from Barniol and Zavala (2014b)	DL	SE	Infit		Outfit		PTMEA
				MNSQ	ZSTD	MNSQ	ZSTD	CORR
Q2	Unit vector: Graphical representation of unit vector	2.45	0.47	1.04	0.20	0.76	-0.20	0.18
Q1	Addition: Graphical addition of vectors in 2D	1.53	0.33	0.92	-0.30	0.86	-0.20	0.32
Q13	Subtraction: Graphical subtraction in 2D	1.23	0.30	0.96	-0.10	0.93	-0.10	0.31
Q12	Cross product: Interpretation as a perpendicular vector	1.14	0.30	1.06	0.40	1.12	0.50	0.22
Q3	Dot product: Interpretation as a projection	0.97	0.28	1.02	0.20	1.23	0.90	0.26
Q17	Direction: Determining direction of a vector presented in unit-vector notation	0.97	0.28	1.01	0.10	1.05	0.30	0.29
Q19	Subtraction: Graphical subtraction of vectors in 1D	0.90	0.28	1.01	0.10	1.05	0.30	0.29
Q16	Addition: Comparing magnitudes that involve addition of vectors	0.82	0.27	0.91	-0.50	0.80	-0.70	0.41
Q8	Dot product: Dot product of vectors presented in unit-vector notation	0.48	0.25	0.96	-0.30	0.85	-0.70	0.39
Q9	Component: Representation of x component	0.08	0.23	0.96	-0.40	0.89	-0.70	0.41
Q15	Cross product: Cross product of vectors presented in unit-vector notation	0.08	0.23	0.96	-0.40	0.89	-0.70	0.41
Q7	Addition: Comparing sum of two vectors 90 apart with magnitude of each vector	- 0.08	0.23	1.06	0.60	1.18	1.30	0.30
Q11	Scalar multiplication: Multiplication with a negative scalar	-0.39	0.22	0.96	-0.50	0.89	-0.90	0.43
Q4	Component: Graphic representation of y component	-0.72	0.22	1.14	1.80	1.17	1.60	0.26
Q14	Component: Calculating of x component of a vector with angle measured from y-axis	-1.10	0.22	1.00	0.00	1.03	0.30	0.39
Q10	Vector representation: Representation of a vector written in a unit-vector notation	-1.24	0.22	0.99	-0.10	0.99	0.00	0.41
Q18	Cross product: Calculating cross product using formula AB Sinθ	-1.34	0.22	0.98	-0.20	0.94	-0.50	0.42
Q5	Direction: Choosing a vector with same direction	-1.75	0.23	1.03	0.30	1.02	0.20	0.37
Q20	Magnitude: Magnitude of a vector presented in a unit-vector notation	-1.97	0.24	0.98	-0.20	0.91	-0.40	0.42
Q6	Dot product: Calculating dot product using formula AB Cosθ	-2.08	0.24	1.03	0.30	1.00	0.10	0.36

Note. DL: Difficulty in logits & SE: Standard error

of difficulty indices, with the difficulty indices ranging from -2.08 (Q6: the easiest question) to 2.45 (Q2: the most difficult question). However, the item/person map also shows that the difficulty of test questions did not perfectly target the abilities of participants, as most of the participants were unable to answer Q1, Q2, Q13, Q12, Q17, Q3, Q19, and Q16 correctly.

The infit and outfit mean square (MNSQ) values (**Table 1**) were within the acceptable range of 0.5 to 1.5, indicating that the data were productive for measurement (Linacre, 2002, 2003).

To answer the first research question regarding the difficult concepts, the difficulty indices of the test questions were estimated in logits, as shown in **Table 1**.

As shown in **Table 1**, the students appeared to find several questions and concepts easy. The easiest concept was the magnitude of a vector (D=-1.97 logits). Other easy concepts were choosing a vector with the same direction (D=-1.75), calculating the cross product from the formula (D=-1.34), the representation of a vector presented in a unit-vector notation (D=-1.24), and calculating x-component of a vector using the angle measured from y-axis. On the other hand, they appeared to find several items very difficult. The graphical representation of unit vector was the most challenging concept: the estimated difficulty (D) of Q2 was 2.45 logits, the highest level. Graphical addition in two dimensions (D=1.53 logits) and graphical subtraction in two dimensions (D=1.23 logits) were also difficult concepts for the participants. Other concepts they appeared to find difficult included the interpretation of the cross product as a perpendicular vector (D=1.14), the interpretation of the dot product as a projection, and the direction of a vector presented in unit-vector notation (D=0.97 logits).

The second research question investigated whether differences in students' understanding of vector concepts could be attributed to their gender or their choice of major. To analyze the data and address the second research question, the ability (performance) of each student was estimated in interval logits using Winsteps software, then the differences between means were investigated using SPSS. Mean (M) and standard deviation (SD) of ability to understand vector concepts were M=-0.93 and SD=0.87 for females and M=-0.81 and SD=1.17 for males. To investigate the differences between the means, an independent sample t-test was conducted. The results of the t-test (t=-0.54, df=95, p=.59) showed that there was no statistically significant difference (α=0.05) between the means; and therefore, no significant differences in mean ability to understand vector concepts can be attributed to the gender of the students. Moreover, the independent sample t-test was used to investigate whether there were significant differences between means that could be attributed to the students' chosen major (science or engineering). M and SD of ability to understand vector concepts were M=-1.15 and SD=1.03 for science students (n=36) and M=-0.71 and SD=0.86 for engineering students (n=55). The results of the t-test (t=2.19, df=89, p=.031) showed that there was a significant difference (α=0.05) between the two groups' mean ability to understand vector concepts; engineering students performed significantly better than science students in this regard.

DISCUSSION & RECOMMENDATIONS

The results indicate that the participants found several concepts easy to understand (**Table 1**). They demonstrated an understanding of how to calculate scalar multiplication, calculate the dot and cross products using formulas, calculate the magnitude of a vector presented in a unit-vector notation, and calculate x-component of a vector using the angle measured from y-axis, among other concepts. Susac et al. (2018) also found that certain concepts such as scalar multiplication, vector components, and calculation of the magnitude of a vector, appeared easy to their sample; this indicates that students find it easy to understand these concepts. While calculating the dot and cross products using formulas appeared to be easy for participants in the present study and in other studies (e.g., Susac et al., 2018), interpretation of the dot and cross products was challenging for them.

As most of the participants were unable to answer Q1, Q2, Q13, Q12, Q17, Q3, Q19, and Q16 correctly (**Table 1**), the author identified two main groups of difficult vector concepts. The first group of difficult vector concepts relates to graphical representation when performing basic operations, such as the addition and subtraction of vectors (Q1, Q2, Q13, Q17, and Q19). The second group of difficult concepts cover the difficulty of interpreting the dot product and cross products (Q3 and Q12).

The graphical representation of vectors when conducting basic operations was challenging for the participants. The most difficult concepts included the graphical representation of a unit vector, the graphical addition of vectors in two dimensions, and the graphical addition of vectors in two dimensions. Other related studies found that the unit vector was a very difficult concept (Barniol & Zavala, 2012, 2014a). Sirait and Oktavianty (2017) also found the addition and subtraction of vectors when they were presented in two dimensions to be difficult. It appears that the graphical representation of vectors, or switching between representations of vectors, might be the reason why the addition and subtraction of vectors appeared to be very difficult for students (Latifa et al., 2021). It is recommended that physics instructors should pay extra attention to the graphical presentation of vectors and find effective ways of switching between algebraic and graphical representations. To help students make connections between algebraic and graphical representations of vectors, instructors may implement interactive puzzles in a non-traditional creative environment (Klein et al., 2018). Students may need to practice extensively in order to perform the graphical addition and subtraction of vectors correctly.

The second group of difficult concepts related to difficulties in interpreting dot and cross products. It was found that while performing the dot and cross products using the formulas was easy for the students, interpreting the dot and cross products was difficult. Physics instructors may have overemphasized the calculation of the dot and cross products over their interpretation and meaning. Therefore, it is recommended that physics instructors assign additional instruction (Nguyen & Meltzer, 2003) and pay extra attention to the interpretation of the dot product as a projection and the cross product as a perpendicular vector. In addition, tutorial worksheets on the interpretation of the dot product may be used, which may help students to develop their understanding and interpret the dot product correctly (Barniol & Zavala, 2016). To improve the teaching of vector concepts and overcome students' difficulties in understanding vector concepts, it is recommended that physics instructors implement new pedagogical teaching interventions such as peer instruction (Ouko et al., 2015), the use of multiple representations (Munfaridah et al., 2021), interactive computational systems (Karnam et al., 2018) and interactive games (O'Brien & Sirokman, 2014).

The present study found no significant differences in students' understanding of vector concepts that could be attributed to their gender (males and females, in mixed classes). The aforementioned interpretations and recommendations can therefore be applied to both male and female students. Engineering students performed better than science students in understanding vector concepts, even though students in both groups joined the same mixed-major classes. This difference in performance may be attributed to initial differences in students' abilities in the context of Jordanian universities; the high school final year exam grades of students who join engineering majors are usually higher than those of science students. It is recommended that instructors pay extra attention to science students in general and physics students in particular when teaching vector concepts, as understanding vector concepts is necessary to master many other concepts and topics in physics.

Recommendations for Future Research

Physics education researchers are invited to conduct further studies to fully understand difficulties in dealing with graphical representations, as well as interpreting the dot and cross products, and to introduce research-based teaching methods and materials that may help students to overcome these challenges. Latifa et al. (2021) also called for researchers to identify appropriate learning systems for overcoming difficulties in understanding vector concepts when vectors are graphically represented.

Researchers in Jordan are invited to administer TUV several times across different semesters in order to obtain more robust and generalizable results. Moreover, there is a need to conduct research that provides an in-depth understanding of differences in the understanding of vector concepts between engineering and science students in Jordan; research that can likely be achieved by conducting qualitative studies.

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Declaration of interest: No conflict of interest is declared by the author.

Data sharing statement: Data supporting the findings and conclusions are available upon request from the author.

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