Paper

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Superposition of vectors and electric fields: a study using structured inquiry tutorial lessons with upper secondary level students

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Abstract

Tutorials in introductory physics (TIP) are a well known resource for use in third level insititutions for developing students' understanding of physics concepts. However, this resource is only sparingly used at second level. This study presents an adaptation of the approach taken in TIP to enhance the understanding of vector addition of a group of upper secondary students. The results present qualitative evidence of the development of the students' understanding of vector addition. Issues surrounding the application of their understanding to an electrostatics context are also examined. Our results indicate that the approach taken in TIP can improve student learning at second level, and contribute to the small body of literature on this topic.

1. Introduction

Tutorials in introductory physics (TIP) have been widely used in US universities [1]. When they were implemented in German universities, it was observed that the material covered in TIP would be better suited for upper second level physics instruction in the German education system [2]. However, literature on using the approach at second level is sparse, with only one example of implementation in Argentinean high schools recorded by Benegas and Flores [3]. They employed two tutorials from TIP, 'current and resistance' and 'potential difference'. Their results indicated that the use of TIP at second level resulted in higher conceptual gains than in their control group. However, their study reports only the student gains quantitatively, and does not give qualitative insight into the development of students' understanding prior to, during, or after instruction.

In contrast, the study presented in this paper provides qualitative evidence of students' developing understanding of electric fields during implementation of a series of tutorial lessons based patterned after TIP. The use of pre-tests, post-tests and tutorial worksheets enabled us to probe, develop and assess student understanding before, during, and after instruction. The tutorial sequence relies on the use of vector addition, and we probe our upper secondary students' understanding of vector component addition applied in an electrostatics context. Nguyen and Meltzer [4] discussed common problems they observed in students' understanding of vector addition in two dimensions. These difficulties include adding magnitudes as in scalar addition instead of vector addition, not taking into account the relative direction of vectors, not conserving vertical / horizontal components, and not acknowledging their contribution to the resultant vector and using a 'split the difference' algorithm, in which the resultant is always along the bisector of two vectors, regardless of their magnitude. These difficulties are illustrated in figure 1.

2. Methods

2.1. Research questions

The aim of this study is to provide a qualitative body of evidence to demonstrate the effects of structured inquiry lessons implemented in an upper secondary physics classroom on students' conceptual understanding of superposition in the context of electrostatics. The following research questions are addressed:

i. How does students' conceptual knowledge of vector addition change over the course of implementing structured inquiry lessons?
ii. To what extent are the structured inquiry lessons effective in promoting conceptual change?

The study presented in this paper contributed to a larger overall body of research, focusing the development and assessment of student's conceptual understanding of electrostatics in upper secondary physics [5].

2.2. Research context

This research took place in a secondary school in Ireland, with a group of 14 mixed ability upper secondary students, aged 16–17 years. All students were assigned, and are referred to by, a letter to ensure that their identities would be anonymous when reporting on the research. The group is mixed gendered, but predominantly male (female = 4 students, male = 10). The school the students attended is in a rural community. This school is designated as a DEIS school, which implies that a high percentage of the entire student body comes from socio-disadvantaged backgrounds.

2.3. Approach to teaching and learning

The pedagogical approach adopted in this study was structured inquiry [6], implemented using a methodology adapted from the teaching & learning experiences employed in TIP [1].

According to Banchi and Bell [6], structured inquiry occurs when there is no pre-determined conclusion known to the learners when they commence a task. The outcomes of learning and understanding are based on the learners' construction of knowledge through whatever learning activity was completed. The learning activity itself is designed to lead the learners' thinking towards a specific learning outcome or set of outcomes, but the learners are required to reach this outcome with little instruction from the teacher. Tabak *et al* [7] indicate that the use of structured inquiry learning promotes the development of students' conceptual understanding of target concepts. This is also evidenced by Blanchard *et al* [8] and Jiang and McComas [9]. The latter study used PISA 2006 data to show that Level 2 activities, in which students conduct activities and draw conclusions from data, but the teacher designs investigations and asks questions, correlate most strongly with science achievement and positive attitudes. This distribution of responsibilities is characteristic of TIP.

TIP [1] is a set of supplementary activities to accompany lectures or a standard textbook in a standard university physics course. The emphasis is on student understanding of concepts and scientific reasoning skills, as opposed to rote learning theory or solving quantitative problems. Typically, a tutorial consists of a pre-test, tutorial lesson, homework assignment and a post-test. There are countless examples of published research that attest to the efficacy of TIP, including recent publications that attest to the efficacy of the approach [10–12]. These studies present pre-test & post-test data, which indicate the extent to which conceptual development occurred. Additionally, they present excerpts of learners' responses to tutorial lessons, homework assignments and teaching and learning interviews, making the learners' thinking visible and presenting evidence for the process of development of understanding. In this study, implemented at second level, the use of TIP directly was avoided, as that material is aimed at a third level learners. Instead, pre-test and post-test questions were adopted and adapted to use in this study, and the tutorials used in this study were drafted and implemented in the same style as TIP.

The approach taken in this research focused on promoting our student's conceptual understanding using a conceptual change framework. Konicek-Moran and Keeley [13] consider learners demonstrate conceptual understanding when they can think with a concept, use the concept in other areas to that in which they learnt it, state it in their own words, find an analogy or metaphor for it and can build a mental or physical model of it and explain it. When learning about natural phenomena, in both formal and informal settings, misconceptions can be developed. They can become deeply engrained in mental models and are resistant to change. By promoting conceptual change in the learner's models, these misconceptions can be challenged and overcome. Hewson [14] suggests three mechanisms in which conceptual change can occur. Conceptual extinction when an idea is replaced to the point where it is forgotten. Conceptual exchange where an idea remains but its' status is lowered over a newer idea and is disregarded in favour of the more useful robust idea. Conceptual extension is where a person incorporates a new idea into their existing understanding and reorganises their existing knowledge to account for the new knowledge. Posner *et al* [15] proposed four conditions necessary to promote conceptual change in student learning:

i. There must be dissatisfaction with existing conceptions.
ii. The new conception must be intelligible
iii. The new conception must be initially plausible
iv. A new conception should suggest the possibly of a fruitful research programme.

The last of these conditions is not directly related to the students that took part in this study, as research programmes were not apart of the lesson sequence that they took part in. However, when reviewing the student's responses that they could find the new concept to be fruitful, in so far as it was useful to them when explaining physics principles when completing the tutorial lessons.

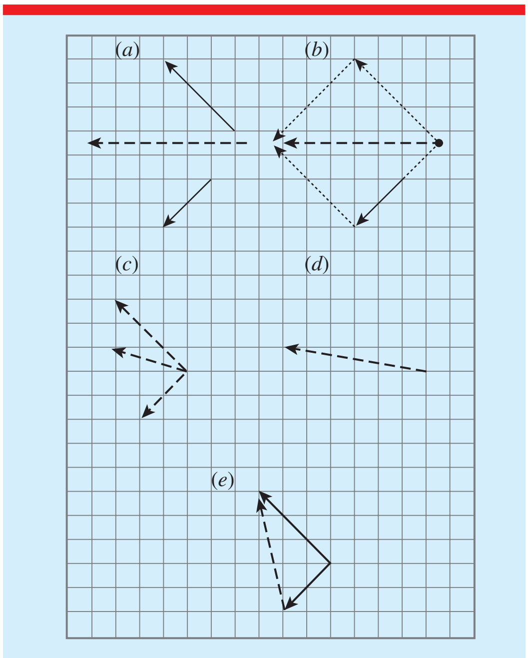

Figure 1. Illustrations of student errors during vector addition (a) zero vertical vector components (b) 'split the difference' (c) incorrect parallelogram addition (d) incorrect horizontal component and (e) tip—to—toe error (Nguyen and Meltzer [4]).

As the sample size of the students is small ($N = 14$), descriptive qualitative data analysis was used. This allowed for a narrative description for analysing the learning process that occurred during the tutorial lessons applied to be generated. Pre-test and post-test comparisons allow for judgements on whether conceptual change has occurred, and analysis of the student's tutorial lessons, and homework assignments allowed for the indication of how the student's conceptual development occurred. The student artefacts were used to populate the tables of results of student responses and identify concepts/misconceptions which were visible in the student's thinking. The data was also used to determine whether students are using key concepts in their correct contexts or overlapping their understanding [16]. In doing so, instances of conceptual change are identified, and the extent to which it occurred can be gauged.

Four descriptors are drafted in this study, with the purpose of indicating the extent to which conceptual change occurred, as shown in table 1. The four descriptors were based of dividing the number of students into quartiles. These descriptors were minimal, partial, moderate and ideal. Minimal conceptual change refers to instances in which between one and three students demonstrated that conceptual change occurred. Partial conceptual change refers to instances where between four and seven students were observed to have engaged in conceptual change. Moderate conceptual change is referred to when between eight and eleven students engage in conceptual change and ideal conceptual change is referred to when between twelve and fourteen students demonstrate conceptual change.

3. Results

3.1. Vectors pre-test

The students completed a conceptual vectors pre-test question to determine their understanding of vector addition. The question was originally published in TIP [1]. In this question, as shown in figure 2, the students were asked to state which body experiences the net force of largest magnitude and explain their choice. This question was seeking to elicit whether the students would apply scalar addition or vector addition to the three force diagrams shown. A summary of the student's responses is presented in table 2.

Eight of the 14 students added the vectors as if they were scalars, not accounting for the how direction of vectors would affect the net force. Although they were familiar with the concept from previous classes, no students referenced the horizontal or vertical vector components, and considered how they would sum together. Student reasoning was consistent with regards to the magnitudes of the forces summing directly to have an equal net force.

Student B:	*I think all the forces are the same because:* $8 = 8$, $4 + 4 = 8$, $2 + 2 + 2 + 2 = 8$.
Student C:	*They're all the same* $8N = 4N + 4N = 2N + 2N + 2N + 2N$.

Table 1. Outlines of the frequencies of students that relate to the qualitative descriptors which indicate the extent conceptual change that occurred.

Descriptor	Student frequency
Minimal	0–3
Partial	4–7
Moderate	8–11
Ideal	12–14

Table 2. Frequency table of how the students responded to the vectors pre-test question.

Concepts used	Student responses
Vector addition	1
Scalar addition	8
More angles mean more force	1
No reasoning submitted	4

Only one student, H, attempted to use vector addition to complete this question, although there were errors seen in their use of the parallelogram rule when the four vectors were acting simultaneously on the body.

3.2. Vectors tutorial

In the tutorial, the students were guided to interpret vectors and adding vectors graphically and mathematically. Initially, students were guided through the labelling and drawing two vectors, $\vec{a}$ and $\vec{b}$, on a coordinate plane and then sketch the vector components for each of these vectors. Upon sketching the components and producing two right angled triangles, the students had to apply Pythagoras' theorem using the components to determine the magnitude of the two vectors, $\vec{a}$ and $\vec{b}$. The students then moved onto the section of the tutorial in which they would explore vector addition.

The students guided to apply the 'tip to tail' method to construct the resultant vectors graphically. Initially, they did this with collinear vectors, as seen in figure 3(i) with $\vec{c} + \vec{d}$. When completing the vectors in figure 3(ii), the students initially were required to sketch the horizontal and vertical components of the two vectors and combine these to construct the resultant vector. All the students encountered difficulties when attempting this. Eight of the students attempted to add the magnitudes of $\vec{e}$ and $\vec{f}$ directly to produce the resultant, while the remaining six asked for

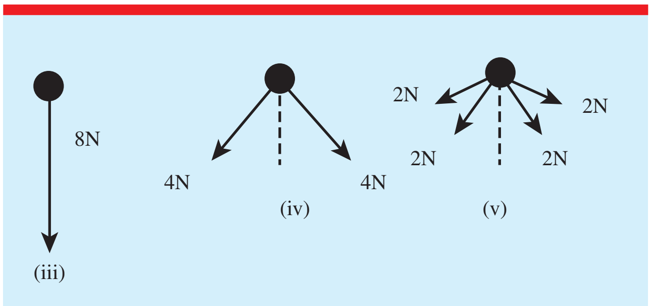

Figure 2. Vectors conceptual pre-test question, in which they were asked to identify which body would experience the net force of largest magnitude.

assistance in completing this section. In all cases, the teacher requested the students sketch the horizontal and vertical components for $\vec{e}$, and then $\vec{f}$. Students were prompted to consider the resulting horizontal magnitude if they combined the horizontal components only, and then apply the same reasoning to the vertical components. With these prompts, the student was able to construct the resultant vector.

The students were then required to find determine the resultant vectors for those presented in figures 3(iii) and (iv) in the same manner. Upon completing this part of the exercise, students were asked to explain, in their own words, why the magnitudes in setup (iii) could be added directly and why they could not be added directly in (iv). Although it took time for the students to articulate their answers, the only guidance needed was to highlight the keywords required to give a full answer (horizontal and vertical components, magnitude, resultant), and they were able to construct their own valid meaning to this question. The following example of a teacher—students discussion illustrates this type of intervention.

Teacher *(reading student's work)* '*Because they are not going in the same direction so the*' ... *ok, so the direction is important?... Ok I'm going to show you some keywords for your answer. (*Teacher highlights the words horizontal and vertical components on the tutorial page*)*.

∗∗Teacher allowed students to work on this section for 5 minutes before returning. ∗∗

Student K:	*Is it cause the horizontal components are going in different directions?*
Student L:	*Yeah*
Student J:	*Well, I said, that way one goes up and then it returns, so then it is equal to zero. Like four plus six would be equal to ten, but we're taking them away, so I said it is zero here. This is why there is like, no change there.*
Teacher:	*I did not hear you, what were you saying?*
Student J:	*Nothing* (brief laughter)
Teacher:	*No, go with it. It sounded like you were right, I just came in at the end.*
Student K:	[J] *was saying that these parts are going in a different direction.*
Student J:	*And it is returning, so there is no change…*
Teacher:	*There's no change in what?*
Student L:	*In the horizontal components.*

3.3. Vectors post-test

The vectors post-test question was designed to determine what conceptual understanding students had of adding vectors at angles. Students were given a scenario where an object was being pulled by two ropes, all with the same magnitude. Students were required to determine which of the three scenarios showed the strongest net force acting on the object and the weakest net force acting on the object. The questions are depicted in figure 4, and the reasoning used by the students is presented in table 3.

The post-test results show that all but one of the students correctly determined the correct outcome. Where the students provided both justifications for their answers, it was seen that

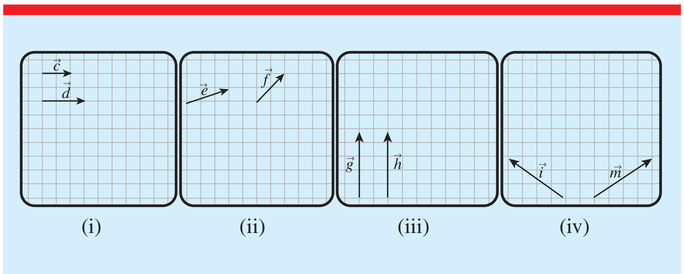

Figure 3. Extract from vectors tutorial lesson in which they compared the addition of various pairs of vectors.

students tended to refer to both their diagrams and the components in their reasoning. This would suggest to us that students are not completing the constructions as a matter of rote—learned procedure but indicate that the students can determine the utility in both answering the question using vector constructions and in terms of the combination of vector components. Other students chose to reference the horizontal vectors alone and did not attempt to generate evidence for their reasoning using the parallelogram/tip to tail method.

Student B:	[(a)]. *Both forces are acting the same direction, meaning there are no opposite forces cancelling out.* *Diagram* [(c)] *shows the weakest force as there are large horizontal component forces cancelling out meaning there is less vertical component forces.*
Student K:	*The third one,* [(c)]. *Even though the second one has a vertical and horizontal component, the third one has a wider horizontal component, so the force has to act on two difference horizontal.*

Other students submitted the correct answer but gave incomplete reasoning that suggested the use of horizontal and vertical components, but lacked clarity and the use of keywords in the explanation:

Student E:	*A would allow a pulling power of 1000 N, as the combination of the two forces pulling in the same direction would be greater than that of two pulling in different directions and cancelling each other out to a degree.* [*Diagram*] C [*is the strongest*]. *The forces are pulling in moderately different directions, which causes them to weaken the pulling power, by cancelling most of what the other is doing.*

Table 3. Frequency table of how the students responded to vectors post-test question.

Concepts used	Student responses
Parallelogram/tip to tail	3
Horizontal and vertical components explicitly referenced.	10
Horizontal and vertical components suggested / answer incomplete.	3
Angle affect magnitude	1

3.4. Vector components in a Coulomb's law context

The students also completed a homework question, in which they could apply their understanding of vector components to a conceptual force question, presented in figure 5. The students were asked to compare the net force acting on the -1 C charged body in (a) with that of (b), and then with that of (c). The question invited the students to use whatever reasoning they deemed appropriate and suggested vector reasoning, calculations or any other reasoning deemed fit by the students. While the vector nature of Coulomb's law was discussed in the class discussion before the tutorial, the tutorial itself did not directly look at the vector nature of electrostatic forces. This question tested if students could transfer their reasoning of vector component directly to the electrostatic context without explicitly exploring it in the tutorial. A summary of the student's responses is shown in table 4.

None of the students gave a complete answer: the horizontal components in (a) cancel, resulting in a net magnitude less than (b), and that the horizontal forces in (c) would sum to zero. Student K, when describing the forces in diagram (a), acknowledged that there is a combination of horizontal and vertical vector components acting

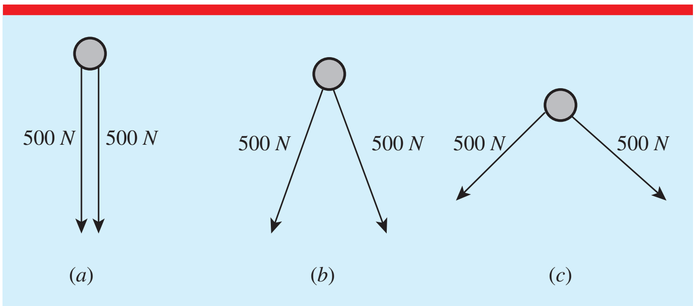

Figure 4. Vectors conceptual post-test question in which they were asked to identify which body would experience the net force of largest magnitude.

Table 4. Frequency table of how the students responded to Coulomb's law vector homework question.

Student reasoning	Students
Applied vector component reasoning	n/a
Applied incomplete vector component reasoning	1
Applied scalar reasoning.	2
Described forces in terms of attraction and repulsion.	1
N/A	10

on the negatively charged particle, while only vertical and horizontal vectors act on negatively charged particle in (b) and (c). However, they stated that the net force is stronger in both cases (b) and (c) and did not consider that the horizontal net force is zero in (c).

Two students used the equation $F = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{d^2}$ in all the setups, and in setup (c) treated the two positively charged bodies as one charged body with a magnitude of +2 C. One of them also that the force would be slightly reduced due to the repulsion between both positive charges, but did not explain this in any detail. Another student interpreted the question to explain whether attraction or repulsion existed between the different combinations of charged particles. The remaining students, bar three who were absent and unable to complete the homework, did not make headway with the question. They stated that they were unaware how to approach the question. This indicated that the suggestion to use vector reasoning or calculations did not prompt them to use the understanding they had previously developed in the electrostatic context.

3.5. Teaching and learning interview - student's use of vector components in Coulomb's law

As the students struggled to transfer their reasoning to the Coulomb's law context, a small group of them were chosen for interview to determine how they could be prompted to correctly approach the question. The students were told they were permitted to ask questions during the interview to help them along, but they were not permitted to ask directly for the solution.

At the beginning of the interview, students A, B and H stated that the forces would be equal in all cases as the −1 C charged particle was being attracted by a net charge of +2 C, in all cases. However, upon being informed that their reasoning was incorrect, and the net force on the particles was not equal in all cases, they considered the use of vectors to analyse the question. The following interview extract illustrates the student's reasoning.

Student H:	*The distance is there* [a] *cause that one will be pulled down the centre line. That is just as strong as charge* [b], *but it is is the most [strongest force], cause it is direct. And that one will cancel out* [c], *so it'll be zero. That one* [b] *will be twice as much if that was one* [c].
Teacher:	*So, C = zero. Why did you say that?*
Student B:	*Cause it cancels out.*
Teacher:	*What cancels out?*
Student H:	*The horizontals.*
Teacher:	*Ok... so now we have horizontal vectors. What type of vectors do we have acting here* [b]*?*
Student A:	*Vertical vectors.*

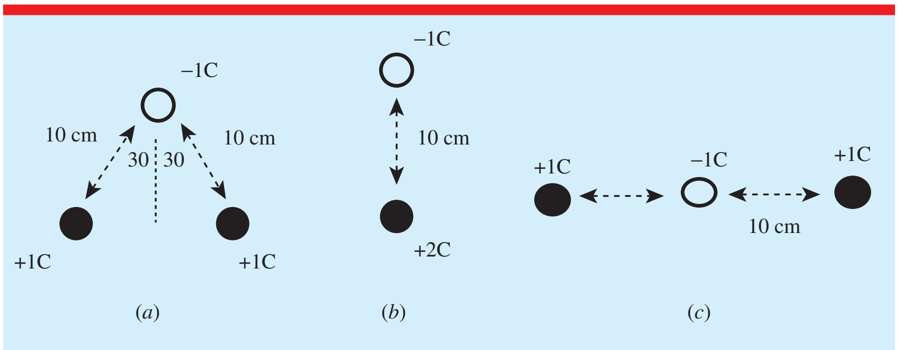

Figure 5. Coulomb's law homework designed to elicit student's transfer of vector addition concepts to electrostatics by ranking the magnitudce of the net force acting the the −1 C charges.

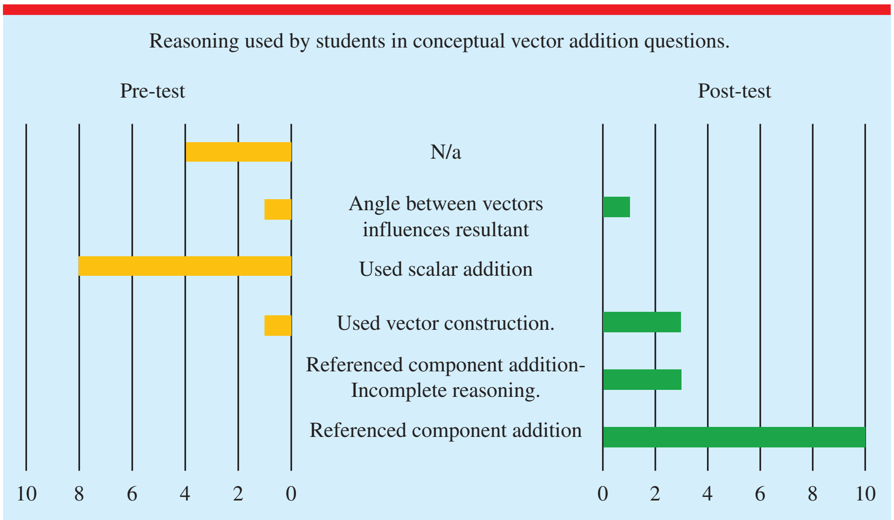

Figure 6. Pre-test/post-test comparison of how the students responded to conceptual vector addition questions.

Teacher:	*And everything is vertical?* [Students nod in agreement] *Ok, so let us just say here* [one horizontal vector is sketched on c] *is 10 N, and this [vector sketched acting in opposite direction] is 10 N, now what's the force acting on this* [b]*?*
Student H:	*20 N.*
Teacher:	*Ok, so look here* [a] *and ignore this [right positive charge]. What force acts on the negative charge?*
Student B:	*10 N.*
Teacher:	*Now ignore this* [left positive charge] *What's the force?*
Student B:	*10 N.*
Student H:	*And we can add them tip to tail now.*
Teacher:	*We can, but also, consider, you mentioned horizontal and vertical components earlier. Keep the idea of components in your head. Do you think the 10 N and 10 N will sum to 20 N?*
Student B:	*The horizontal components in that one* [a] *will cancel out.*
Teacher:	*So, you're only left with what?*
Student H:	*Just vertical components.*

When the students had to consider alternative reasoning, they resorted to vector reasoning without much prompting. The student's reasoning was based on how the component vectors combined. Based on this, they produced an accurate ranking of B > A > C = 0, to represent the net force on the negative charge in each layout.

4. Discussion

The vectors pre-test showed student predominately applied scalar addition when vector addition was appropriate. This was expected as this was as this was the student's initial introduction to the use of vectors in their physics course, and these difficulties are typically seen in literature [4]. In the tutorial lesson, it was observed that the students developed an understanding of components of the vectors, and they considered how these components affect the resultant of a vector. The discussion quoted in the vectors tutorial section of the results shows how the students required time to consider and discuss how all the components affected the resultant, and how the horizontal components summed to zero. In highlighting the reasoning used by the students was not complete, the teacher provided a source of dissatisfaction in the initial reasoning [15], as students would realise the reasoning that they provided would not provide an accurate outcome to a tutorial task. They then discussed alternatives amongst themselves. In a previous question, they had mathematically shown that the horizontal component vectors can sum to zero, leaving a vertical vector as the resultant, but the students did not initially consider this as evidence to support their reasoning in the final question of the tutorial. When students were prompted to review all their previous answers, and to consider what their mathematical answers could tell them about the resultant vectors, they developed reasoning that was plausible and intelligible [15] to provide an accurate and well thought out reason to the task.

The post-test results indicate this teaching approach was effective, as essentially all students gave the correct answers to the final conceptual vector question, with most of the students referencing the horizontal and vertical component summation in their answers. The increase in students explaining vector addition in terms of vector components and reduction of students applying scalar addition, as seen in figure 6, suggests the students engaged in conceptual exchange [14] over the course of this tutorial. The increase in correct student responses and reasoning is indicative of moderate conceptual change having occurred. The vectors tutorial section of the results detailed the reasoning produced by the students and the jump from zero to ten students, in the pre-test and post-test, producing reasoning based on vector addition is evidence to support this.

When vector concepts were applied in an electrostatic context, student errors were once again visible in their responses. The interview with the three students showed the teacher did not need to correct the students, nor volunteer any reasoning the students did not mention themselves. Instead, they were guided to use the reasoning they were suggesting in the three different layouts. This guidance would indicate that they may not have been confident to use it initially, but the prompting allowed them to explore their thoughts, without fear of producing incorrect explanations. Therefore, the issue may not have been their understanding of vector addition but recognising its applicability in an abstract context they were not particularly familiar with.

5. Conclusions

The sections of the inquiry tutorials shown in this paper focused on developing student's conceptual understanding of vector addition in terms of superposition of the vector components and how it can affect the resultant magnitude of two, or more, vectors. As upper secondary physics in Ireland is an algebra-based course, these concepts were developed without utilising specific vector notation or operations. The student's mathematical ability, or lack thereof, may have impeded the depth of understanding to which the tutorial lessons could target. Had the students been more familiar with vector mathematics, the opportunity to develop a richer understanding of vectors in a physics context may be been possible. Considering this limitation to construct the boundaries of the vector concepts targeted in this research, the results indicate that the tutorials approach was effective in promoting conceptual change in the student's understanding.

The students understanding of vector addition was extended in the electrostatic context of these tutorials. The inability of the students to correctly apply their understanding in this context suggests an additional barrier to develop complete models of electrostatic phenomena. In this case, the students must process concepts relating to vectors and simultaneously interpret information about electrostatics. Over the course of the Coulomb's law and electric field tutorials, the students revisited the concepts from the initial vector tutorial and transferred them to this context.

In the tutorials shown, the progression of students understanding was made visible in all sections of the lessons. When students completed a section of learning in the tutorial, they were required to check in with the teacher to determine if the correct level of understanding was research by the students, and they could advance or review, depending on their progress. Through review of their dialogues and interviews, their thinking was made visible in a manner that traditional instruction does not typically afford. All this evidence suggests that moderate instances of conceptual change were observed in the student's application of vector concepts to Coulomb's law and the electric field.

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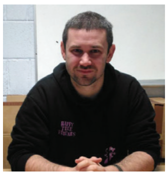

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