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"Let's look at the whole elephant before we begin to measure its tail"*: the effect of emphasising qualitative reasoning in aiding conceptual understanding in a Year 12 physics class

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Abstract

The lack of conceptual understanding that results from traditional physics instruction is a phenomenon that has been well documented by the physics education community. A commonly suggested explanation for this is that the emphasis physics curricula place on quantitative problems disincentivises qualitative understanding and the development of conceptual models. This action research intervention examines the effect of pedagogies which emphasise qualitative reasoning on conceptual understanding, attitudes towards physics and problem-solving confidence. Following a seven-lesson sequence on electric circuits with a Year 12 class, significant improvements in conceptual understanding were observed. The prevalence of common misconceptions decreased, and performance on conceptual questions increased. No significant change in students' attitudes or confidence was observed.

*(Hewitt, 1983, p.311)

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“Let’s look at the whole elephant before we begin to measure its tail”: the effect of emphasising qualitative reasoning in aiding conceptual understanding in a Year 12 physics class

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Introduction

How do you turn on a light-bulb using a battery and a wire? This would appear to be a question students leaving a course on electric circuits should be able to answer. Yet students find this question, and many other simple qualitative questions about electric circuits, very difficult (McDermott & Shaffer, 1992a). This is not a problem limited to electric circuits; throughout all of physics education, students perform poorly on qualitative questions when compared to quantitative questions, and often possess misconceptions about fundamental concepts (Cohen, Eylon, & Ganiel, 1982; McDermott 1991; Mazur, 1992). If a goal of physics education is to encourage students to understand the natural world, and not merely to perform algebraic manipulation, this constitutes a serious problem for the physics education community.

As described in the research review, a proposed cause of this problem is the emphasis physics curricula place on quantitative problems. Students who study physics quickly learn that they do not need to understand phenomena, and only need to plug numbers into formulae (Millar & Beh, 1993, Crouch & Mazur, 2001; McDermott, 2011). This action research intervention investigates the effect of putting qualitative questions and conceptual understanding at the forefront of the physics curriculum. Several different pedagogies which emphasise qualitative reasoning, were implemented during a series of seven lessons on electricity with a single Year 12 class of 11 students. Data was collected to determine the effect of these pedagogies on students’ conceptual understanding, attitudes towards physics and problem-solving confidence.

Literature Review

The first section of this literature review discusses an identified problem in physics education: a lack of conceptual understanding. The emphasis on quantitative problems in physics classrooms is addressed as a possible cause of this problem in the second section. The final section considers a possible solution: emphasising qualitative problems.

The problem – a lack of conceptual understanding

The lack of conceptual understanding that results from traditional physics instruction is a phenomenon that has been well documented by the physics education community. While students leave physics courses with the ability to solve typical quantitative problems, researchers find that the same students hold misconceptions which persist throughout all stages of education (McDermott 1991; Van Heuvelen, 1991; Mazur, 1992; McDermott & Shaffer, 1992a). The widespread use of conceptual tests such as the Force Concept Inventory (FCI) (Hestenes, Wells, & Swackhamer, 1992) and the Determining and Interpreting Resistive Electric Circuit Concepts Test (DIRECT) (Engelhardt & Beichner, 2004) has raised awareness of the fact that students leave physics courses with incorrect ideas about the way the world works. If a goal of physics instruction is to encourage students to understand the world around them, and not just to perform calculations, then the findings of the physics education community are a cause for great concern which must lead us to question the way in which physics is taught.

The topic of electric circuits has been studied extensively to determine the misconceptions which students come to hold, and it is clear that similar misconceptions arise in different education systems at different levels of experience (Dupin & Johsua, 1987; McDermott & Shaffer, 1992a). In a study of 15-17 year old students in five European countries, Shipstone et al. (1988) found that students in different education systems experienced similar problems, which “suggests that there is an almost 'natural' coherence to the learning difficulties within cognitive structure” (p.315). It appears that the concepts of electric circuits are difficult for the brain to accept, and that instruction does not resolve these difficulties adequately. The prevalence of misconceptions about electric circuits is largely unaffected by instruction (Engelhardt & Beichner, 2004) and in some cases those who have had experience with electric circuits hold more misconceptions than novices (Goris & Dyrenfurth, 2013).

General difficulties with electric circuits concepts

McDemott and Schaffer (1992a) describe three general difficulties students encounter when trying to understand electric circuits:

a. Failure to distinguish among related concepts

Students often refer to voltage, current, energy and power incorrectly and interchangeably (McDermott & Schaffer, 1992a; Engelhardt, 1997; Afra, Osta, & Zoubeir, 2009). For example, students will describe both current and energy as being 'used up' around a circuit (Shipstone et al., 1988; Goris & Dyrenfurth, 2013). Students will also claim that both voltage and current are 'split' at junctions in parallel circuits (Millar & Beh, 1993).

b. Lack of concrete experience with real circuits

Students have little or no observational base they can draw upon when forming ideas about how electric circuits work (McDermott & Schaffer, 1992a). This lack of experience with real circuits means students find it difficult to relate conceptual ideas to real circuits. Encountering electricity as a mostly theoretical topic before approaching real circuits also causes students to defend their misconceptions against sensory experience (Arnold & Millar, 1987).

c. Failure to understand and apply the concept of a complete circuit

While most students quickly learn the definition of a complete circuit, many fail to apply the concept (McDermott & Schaffer, 1992a). Students tend to reason locally or sequentially, believing that a change in a circuit only affects where the change occurred or the components 'after' the change, not the entire circuit (Cohen et al., 1982; Shipstone et al., 1988; Engelhardt, 1997).

Specific misconceptions concerning electric circuits

Much research focuses on the specific misconceptions or alternative ideas students have about electric circuits. Taşlıdere (2013) summarised this research into 11 key misconceptions, of which the three most prevalent and persistent are described below:

M2. The attenuation model

This refers to the idea that current travelling in one direction decreases gradually due to consumption of current by devices (Dupin & Johsua, 1987; Shipstone et al., 1988; McDermott &

Schaffer, 1992a; Afra et al., 2009; Taşlıdere, 2013). This belief that current is 'used up' throughout a circuit is often due to the confusion between energy and current as previously discussed (Millar & Beh, 1993).

M8. The power supply as constant current source

This is the belief that the power supply provides a constant current, not a constant voltage (Dupin & Johsua, 1987; Shipstone et al., 1988; McDermott & Schaffer, 1992a; Afra et al., 2009; Taşlıdere, 2013). Current is seen as the primary concept, in that a battery is seen as a producer of current, not a producer of potential difference (Cohen et al., 1982). This idea is the most persistent misconception, and is prevalent at all stages of physics education (Engelhardt & Beichner, 2004).

M9. The parallel circuit misconception

This refers to the idea that a resistor is only an obstacle to current flow. Students assume any increase in the number of parallel connected resistors results in an increase of the total resistance (Cohen et al., 1982; McDermott & Schaffer, 1992a; Afra et al. 2009; Taşlıdere, 2013). Students tend to focus on the number of resistors, rather than their arrangement.

A possible cause – an overemphasis on quantitative problems

Why do students studying electricity, and physics in general, so often leave with misconceptions? Hewitt (1983) argues that the lack of conceptual understanding that results from traditional physics instruction is the result of an overemphasis on quantitative problems. He points to a study in which only 30% of undergraduate students could answer simple qualitative questions about the brightness of bulbs, while 65% of the class could answer more complicated mathematical questions involving Kirchoff's laws (Arons, 1982). This is one example of a widespread phenomenon in all of physics: students perform well on quantitative problems, but poorly on qualitative problems (Cohen et al., 1982; McDermott 1991; Van Heuvelen, 1991; Mazur, 1992). Why is this the case? Surely we would expect students who understand topics to perform approximately equally on qualitative and quantitative questions, indeed perhaps worse on quantitative questions due to the mathematical skills required on top of conceptual understanding.

The reason for this disparity is that quantitative problems are often not a good measure of conceptual understanding (McDermott & Shaffer, 1992a; Gaigher, Rogan, & Braun, 2007). Indeed, several studies have shown that students bypass conceptual understanding altogether when studying physics, in favour of learning mathematical algorithms (McDermott, 2011). University students explain they solve problems not by thinking about physics concepts, but instead "by plugging…values into an equation"; a problem which begins at school (Leonard, Dufresne, & Mestre, 1996, p.1498; Crouch & Mazur, 2001). A study of 157 15-year-old comprehensive school students studying electricity found that "few students use a mental model of voltage in approaching parallel circuit problems but instead attempt to solve problems by mechanical use of the V=IR equation" (Millar & Beh, 1993, p.351). For example. while high-school students can recall a mathematical equation for resistors in parallel, some cannot cannot explain why adding resistors in parallel decreases the total resistance, believing this to be "a mathematical fact" (Cohen et al., 1982, p.408). It appears students are trained to calculate, not to understand; an attitude reinforced by the emphasis that physics curricula place on quantitative problems.

By contrast, students are rarely confronted with qualitative problems, and grow to fear qualitative reasoning due to a lack of experience (McDermott & Shaffer, 1992a; Engelhardt, 1997; Engelhardt & Beichner, 2004). Students lack a conceptual model for predicting the behaviour of circuits, and hence resort to formula memorisation. This is a serious problem if we seek to train successful physicists, as a study comparing the problem-solving strategies of students shows. Those who answer physics problems faster and more accurately rely on conceptual understanding and mental models, whereas unsuccessful students rely on memorized algorithms (Larkin, McDermott, Simon, & Simon, 1980). Students' answers are devoid of the sketches and diagrams which would indicate qualitative thinking (Van Heuvelen, 1991) and the reason why is simple – no qualitative thinking is taking place.

The emphasis on quantitative problems in traditional physics courses not only disincentivises conceptual understanding, but dissuades people from studying physics at all. The perceived mathematical difficulty of physics is a key factor which causes many students not to study physics (Hewitt, 1983; Osbourne, Simon, & Collins, 2003). Furthermore, the longer students study physics, the less students think about physics in a similar way to experts. Use of the Colorado Learning Attitudes about Science Survey (CLASS) shows that the longer students study physics, the less "expert-like" their beliefs become (Redish, Saul, & Steinberg, 1998; Adams et al., 2006; Ding, 2012). The largest disagreement between experts and students is in the "applied conceptual understanding" category, which includes statements such as "When I solve a physics problem, I locate an equation that uses the variables given in the problem and plug in the values." (Adams et al., 2006, p.12; Ding, 2012) Students, unlike experts, view physics as "just formula based" (Sangam & Jesiek, 2012, p.8). Given that there is a strong correlation between expert-like views and further study of physics (Adams et al., 2006), the deterioration of views due to normal instruction is worrying, and may also be due to an overemphasis on qualitative problems.

A possible solution – emphasising qualitative reasoning

> "Facility in solving standard quantitative problems is not an adequate criterion for functional understanding. Questions that require qualitative reasoning and verbal explanation are essential for assessing student learning and are an effective strategy for helping students learn."
>
> (McDermott, 2001, p.1133)

There is considerable evidence to suggest that the emphasis placed on quantitative problems in traditional physics instruction is a leading cause of the well-documented lack of conceptual understanding resulting from instruction. The solution to this problem seems intuitive: to deemphasise quantitative problems and mathematical skills, and put renewed emphasis on qualitative problems and conceptual understanding. Students must be encouraged to develop qualitative thinking skills, to develop conceptual models of physical concepts and to challenge misconceptions in these conceptual models.

Growth in student's reasoning ability does not always result from traditional instruction (Arons, 1982; Redish, 1994; McDermott, 2001). Insistence on the importance of qualitative questions and qualitative reasoning has been shown to encourage students to take this form of learning more seriously, and force them to consider the relationships between variables in non-mathematical ways. Crouch and Mazur (2001) modified their traditional lecture-based undergraduate physics course to deemphasise quantitative problem solving and asked questions designed to uncover reasoning difficulties. They found performance on both qualitative and quantitative questions increased dramatically, despite difficulty in convincing students that qualitative questions were relevant. The relevance of this study to secondary school education is questionable, as students generally encounter conceptual problems more frequently in secondary school than at undergraduate level. Nevertheless, making secondary school students solve complex problems requiring qualitative thinking has been shown to lead to a better conceptual understanding of electric circuits, though this was in the context of 16 disadvantaged South African schools (Gaigher et al., 2007). In order to ease the transition towards qualitative thinking, teachers should explicitly teach qualitative reasoning skills. Larkin (1981) notes that teachers often only explain their thinking verbally, but write down equations on the board. By explicitly sharing qualitative thinking in written form with students, and encouraging students to do the same, increases in conceptual understanding and explanatory skills have been observed in the context of an undergraduate physics course (Leonard et al., 1996).

Students often fail to develop a conceptual understanding of phenomena because little time is devoted to allowing students to develop a conceptual model of such phenomena. A ‘conceptual model’ refers to the ways in which the student is able to imagine a physics phenomenon (McDermott & Shaffer, 1992b). McDermott argues that students must be given the opportunity to engage on a deep intellectual level with physics concepts, and designed the Physics by Inquiry curriculum to allow students to develop their own conceptual model by which they may reason qualitatively (McDermott, 1991; McDermott & Shaffer, 1992b). In the electric circuits module, students spend time with real electric circuits and are encouraged, step-by-step, to visualise how electric circuits work. Quantitative problems are introduced only after a qualitative foundation is established (McDermott, 1996). Implementation of Physics by Inquiry, and similar curricula which emphasise model building such as the ‘rope loop’ model of electricity (DCSF, 2008), has been found to increase performance on conceptual tests at undergraduate level (see Figure 1) (McDermott & Shaffer, 1992b; Brewe, Kramer, & O'Brien, 2008). The applicability of this curricula approach at secondary school level is questionable, as a university laboratory may be a more suitable location for discussion-based practical activities. However, implementation of Physics by Inquiry in a study of twelve 14-15 year old students in a Lebanese secondary school was found to increase performance on DIRECT (Afra et al., 2009). Courses focusing on model-building have also been shown increase the number of students with expert-like views (McKagan, Perkins, & Wieman, 2006; Brewe et al., 2008; Sahin, 2010; Lindsey, Hsu, Sadaghiani, Taylor, & Cummings, 2012).

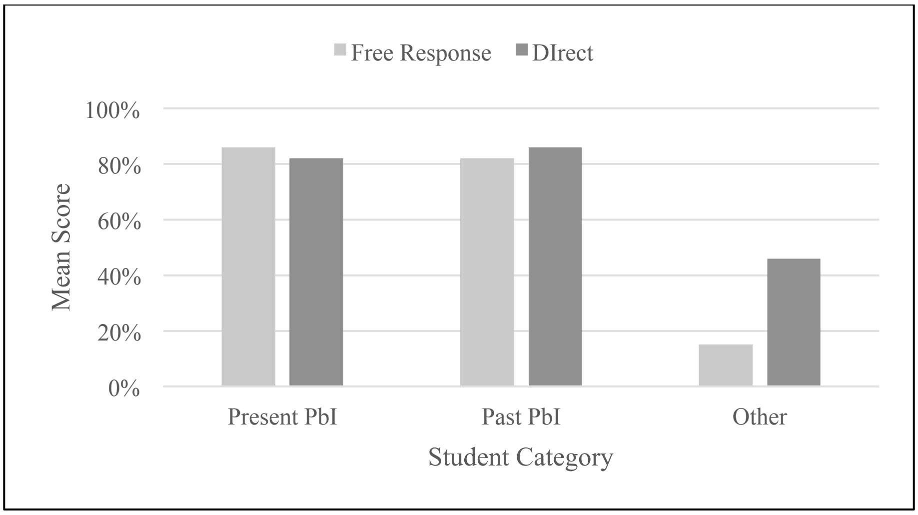

Figure 1: Comparing different students' performance on a free response electric circuits test and DIRECT. Students who are currently studying or have previously studied the Physics by Inquiry (PbI) curriculum perform significantly better. (Redrawn from McDermott, 2000)

It has been shown that for undergraduate students a combination of real and virtual experimentation is more effective in developing a conceptual model of electric circuits than real experimentation alone (Finkelstein et al., 2005; Zacharia, 2007; Farrokhnia & Esmailpour, 2010). Computer programs like the PhET Circuit Construction Kit were designed to "support students in constructing a robust conceptual understanding" by reinforcing "cause-and-effect relationships between voltage, current, resistance and power" (Perkins et al., 2006, p.22). While the effect of virtual experimentation in a secondary school context is largely undocumented, except for one study of gifted students in a Korean school which found a similar increase in conceptual understanding (Lee, Shin, & Kim, 2015), there is little reason to believe the advantages of a virtual experimentation would apply in this context. The ability for students to see electrons in simulations has been identified as a key advantage of simulations in enabling students to construct a conceptual model (Zacharia, 2007).

Once a student has constructed a conceptual model by which they may reason qualitatively, there are likely to be several errors in their model. The term 'conceptual change instruction' describes the processes by which students may alter and correct their conceptual models. Educational theorists have argued that for conceptual change to take place, students must be shown that their existing concepts are unsatisfactory, and presented with a different idea with more explanatory power (Posner, Strike, Hewson, & Gertzog, 1982; Shipstone, 1988; Redish, 1994). Activities should be designed in which a common mistake is deliberately exposed, and then a correct interpretation is arrived at. Implementing this "elicit, confront, resolve" model of conceptual change instruction has been shown to be an effective means of reducing the prevalence of misconceptions (McDermott & Shaffer, 1992b, p.1008). This effect has been observed at undergraduate level (Sangnam & Jesiek, 2012; Taşlıdere, 2013), early secondary school level (Arnold & Millar, 1987) as well as two studies of 16-18 year old students in European secondary schools which are therefore of particular relevance to this study (Dilber & Salar, 2014; Kapartzianis & Kriek, 2014). However, some students, particularly low-achieving students, may view this conceptual conflict as a failure and experience a loss of confidence (Dreyfus, Jungwirth, & Eliovitch, 1990). Students must be encouraged to talk in an honest and exploratory fashion for conceptual change instruction to be effective (Mercer, 1996; Mercer, Dawes, Wegerif, & Sam, 2004; Barnes, 2008). In such an environment, students may experience an increase in problem-solving confidence (Lindsey et al., 2012).

> "Conceptualization should precede computation… Let's look at the whole elephant before we begin to measure its tail"
>
> (Hewitt, 1983, p.311)

Research questions

This report investigates the effect of pedagogies which emphasise qualitative reasoning through encouraging qualitative problem-solving, developing conceptual models and correcting conceptual models through conceptual change. The following research questions are addressed in the context of a Year 12 class studying electricity:

1. Do pedagogies which emphasise qualitative reasoning improve students' conceptual understanding of electric circuits?

2. How do pedagogies which emphasise qualitative reasoning affect students' attitudes towards physics as a subject?

3. How do pedagogies which emphasise qualitative reasoning affect students' problem-solving confidence in physics?

Teaching Rationale

Context

This study took place in an 11-18 academy of approximately 2000 pupils located in England. The school serves a diverse catchment area, and was rated 'Good' in its most recent OFSTED inspection. The class studied were the only Year 12 physics class in the school, consisting of 11 students. Students had a range of previous understanding (see Figure 2). The pedagogies described in this section were implemented during a series of seven lessons covering chapter 10 of the OCR AS-level syllabus titled 'Electrical circuits'. The class' usual teacher had taught the previous two chapters on electricity, which focused on definitions of current, voltage and resistance and components such as filament lamps and thermistors. Chapter 10, which the author of this report taught, focuses on Kirchoff's laws, combining resistors and other methods of analysing more complicated circuits.

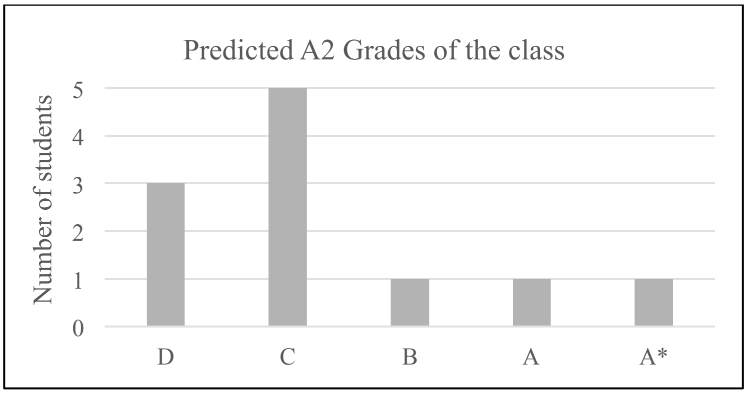

Figure 2: Predicted A-Level grades for the class

Pedagogies which emphasise qualitative reasoning

Table 1 (below) shows the pedagogical techniques that were implemented in each lesson of the 7-lesson sequence.

Lesson	Pedagogy				
	1. DIRECT qualitative questions	2. Physics by Inquiry	3. PhET virtual CCK	4. Conceptual change discussion	5. ‘Solution’ and ‘strategy’ frames
1. Single bulb circuits	✓	✓			
2. A model for electric current	✓	✓			
3. Combining resistors	✓		✓	✓	
4. Kirchoff’s laws	✓		✓	✓	
5. Analysing circuits	✓			✓	✓
6. Internal resistance	✓			✓	
7. Potential dividers				✓	✓

Table 1: The pedagogies implemented in each lesson

Repeated reasoning practise on qualitative questions

Students were given two multiple-choice questions at the beginning of each lesson, and were asked to select an answer and explain their reasoning in writing. The questions were entirely qualitative, not requiring any mathematics to answer, and were selected from the qualitative iteration of DIRECT (v1.0, see Figure 3) (Engelhardt, 1997). Students were then asked at the end of the lesson to answer the same two questions. Giving students an opportunity to change their answers in response to learning has been shown to be an effective way of encouraging students to assimilate conceptual ideas into their own conceptual models, however this effect was studied at undergraduate level where students may be more willing to alter their ideas (Goris & Dyrenfurth, 2013). The questions used in each lesson were relevant to the topic addressed in the lesson, so students had a chance to re-evaluate their ideas. It was hoped, considering the study of 16 disadvantaged South African schools which placed emphasis on qualitative problem-solving

(Gaigher et al., 2007), that repeated practise on qualitative questions would encourage students to take conceptual understanding seriously and develop their reasoning skills.

Compare the resistance of branch 1 with that of branch 2. A branch is a section of a circuit. Which has the least resistance?

a) Branch 1
b) Branch 2
c) Neither, they are the same

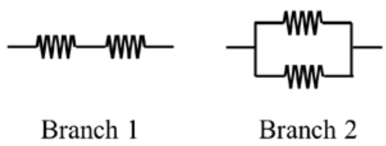

Figure 3. DIRECT question used for the third lesson of the sequence on the topic of 'Combining resistors'. The question is designed to elicit misconception M9. (redrawn from Engelhardt, 1997, p.189)

Inquiry-based building of conceptual models

During the first two lessons of the seven-lesson sequence, students completed Sections 1 and 2 of the Electric Circuits module of the Physics by Inquiry (PbI) curriculum titled "Single bulb circuits" and "A model for electric current" (McDermott, 1996, p.383). Students begin by attempting to light a bulb with a battery and a single wire, before moving on to building more complicated circuits, each intended to develop a particular aspect of their conceptual model of electricity (McDermott & Shaffer, 1992b). Students are asked to articulate their reasoning verbally in small groups of 2-3, and are repeatedly instructed to share and discuss ideas with the teacher (McDermott, 2000). By the end of these lessons, it was hoped that students would have developed a conceptual understanding of how current flows around a circuit, and how resistors in series and parallel affect this flow. While this approach has been shown to be effective at undergraduate level (see Figure 1) (McDermott & Shaffer, 1992b; Brewe et al., 2008), it is largely unknown what effect the Physics by Inquiry curriculum has at secondary-school level aside from a single small-scale study (Afra et al., 2009). At the end of these two lessons, students were asked to compare their ideas about current flow with the 'rope-loop' model of electricity (DCSF, 2008), to assess the strengths and weaknesses of their own understanding of electric circuits.

Building conceptual models through virtual experimentation

In the third and fourth lessons, students used the Circuit Construction Kit (Perkins et al., 2006) to investigate the topics of 'Combining resistors' and 'Kirchoff's laws'. Students worked in groups of 2-3 to construct circuits and measure quantities using on-screen meters. While it seemed likely that the ability to see electrons moving in a circuit would reinforce the conceptual ideas developed in the first two lessons, the effect of virtual experimentation has mostly been studied in a university context (Finkelstein et al., 2005; Zacharia, 2007; Farrokhnia & Esmailpour, 2010).

Conceptual change discussions

At the start of each lesson, excluding the first two lessons, a conceptual change discussion was held using the model of "elicit, confront, resolve" (McDermott & Shaffer, 1992b, p.1008). This was conducted using a similar approach to two studies of 16-18 year old students which have been successful in improving student understanding (Dilber & Salar, 2014; Kapartzianis & Kriek, 2014). Students were presented with an electric circuit, which had been designed to elicit a specific misconception, and were asked how the circuit would respond to a change. In a whole class discussion, students were encouraged to share different ideas and argue what the outcome of the change would be. Once an agreement was reached among the students, or once it became apparent no agreement would be reached, the change was made. Students often predicted what would happen incorrectly, but were then able to produce a correct explanation for the result using ideas discussed in the first two lessons such as the 'rope-loop' model (DCSF, 2008). These conceptual change discussions were intended to encourage students who still held common misconceptions to alter their conceptual models (Taşlıdere, 2013).

Explicit focus on qualitative reasoning

During the fifth, and seventh lessons, typical exam-style quantitative questions were introduced. When answering these questions, students were given a writing frame to encourage students to retain and use their conceptual models, and not to resort to formula and algorithm memorization as many do (Millar & Beh, 1993; McDermott, 2011). This writing frame divided the paper into half, with the left-hand side titled 'strategy' and the right-hand side titled 'solution'. Students were encouraged to write down their qualitative thinking about the problem in the 'strategy' section, and to perform any calculations in the 'solution' section. The teacher also used this writing frame when answering example questions on the board to avoid the issues raised by Larkin (1981). This is the same approach adopted in a different study which increased conceptual understanding and students' ability to justify their answers, albeit in an undergraduate context (Leonard et al., 1996).

Methodology

Action Research

The pedagogies described above represent a significant change from the didactic and quantitative-focused way the class are usually taught. Therefore, this investigation takes the form of action research. As Wilson describes: "When a teacher intervenes to make changes to their practice and at the same time systematically collects evidence of the effects of these changes, then they are engaging in action research" (Wilson, 2009, p.189). Action research is carried out in response to an identified problem (Taber, 2007). In this case the class appeared to lack a conceptual understanding of electric circuits, possibly due to the didactic and quantitative way the class were taught. Action research is usually a cyclical process, with the aim to "arrive at recommendations for good practice that will tackle a problem" (Denscombe, 2007, p.12). This report describes one revolution of such a cycle, to explore whether a change in teaching approach would improve the conceptual understanding in the class and give recommendations for future practice and research which could inform subsequent cycles of action research.

Due to the collaborative nature of the relationship between teacher and student, "the joint concern for action and research can cause serious problems" (Robson & McCartan, 2011). The researcher must ensure that the desire to see an improvement does not cause them to deviate from the intervention which is to be investigated. Action research studies are rarely featured in research journals, perhaps due to the reason that "action research is highly contextualised, and reports may well offer little readily generalised knowledge to inform other practitioners" (Taber, 2007, p.86). This is a concern for this study, where only one class of 11 students was studied.

Ethics

In accordance with recommendations (Bell, 2010; Robson & McCartan, 2011) all students involved in the research project, as well as the Head of Physics and the usual classroom teachers, were informed what form the intervention would take (fewer quantitative questions, more discussion-based practical work and qualitative questions). No decisions made regarding pedagogy were knowingly detrimental to the class' progress. Students and parents of students were given the opportunity to opt-out of any interviews or surveys. Students were assured that all data collected would be treated in accordance with school guidance on data protection, and that all data presented in the final report would be anonymised. Students were asked for consent before being audio-recorded during interviews. This research was carried out in line with the British Educational Research Association (BERA) guidelines for research (BERA, 2011). The Faculty Ethics Form was completed with approval from the Subject Lecturer. Students were generally excited to try a different way of learning. Though, as Bell notes, awareness of being part of a research project may abnormally alter students' behaviour and attitudes towards what is being studied (Bell, 2010).

Data collection and analysis

The research questions posed do not seek to determine which pedagogies emphasising qualitative reasoning are most effective, but rather the combined effect of these pedagogies. Hence, the majority of the data collected focuses on determining students' conceptual understanding, attitudes and confidence before and after the lesson sequence. As there was no control group, it is difficult to be certain the cause of any findings was the pedagogical approach. Focus groups were used as a secondary data source to attempt to determine which pedagogies had been most effective. The following data was collected to answer the research questions, and is summarised in Table 2 (at the end of this section).

CLASS survey

The Colorado Learning Attitudes about Science Survey (CLASS) is a survey which has been used in several previous studies of students' attitudes towards physics (Adams et al., 2006). The survey asks students whether they agree or disagree with 42 statements about physics. These statements ask not just about how much students like physics, but also their views about what physics is. It is then possible to compare students' views with experts, to determine how 'expert-like' the students' views are.

The 42 statements are divided into categories such as 'Personal interest' and 'Conceptual understanding'. Rather than writing the statements to fit into prescribed categories, which may not exist as common patterns of students' thinking, categories were determined by analysing patterns in students' answers to statements (Adams et al., 2004). Consequently, CLASS has been shown to be a robust and useful tool for determining student's views about physics, especially when a particular aspect of students' attitudes requires attention. While all categories were analysed to attempt to answer research question 2, some categories proved useful for other research questions, such as 'Applied Conceptual Understanding' and 'Problem Solving Confidence'.

All 11 students completed CLASS both before and after the lesson sequence, so that the change in views could be measured. The percentage of student views which agreed with experts' views (the favourable views) was determined using the CLASS data analysis tool after the lesson sequence. These percentages were compared with typical data from 397 high-school and university students (Adams et al., 2006).

EPSE test

In order to determine the prevalence of misconceptions before and after instruction, students were given a 10-minute test comprised of 10 multiple-choice questions written by the Evidence-based Practice in Science Education (EPSE) Research Network. These questions "embody insights, and reflect outcomes, of a body of previous research" in that they are designed as a diagnostic probe to elicit common misconceptions, and has been used previously with many secondary school groups (Millar & Hames, 2003, p.2).

From the existing question bank of 50 electric circuit questions, 10 were selected which attempt to elicit the three misconceptions described above. Each question begins by asking a question about an electric circuit, and then asks the student to select a box which explains their answer. Using this explanation, it is possible to determine which misconception caused a student to choose an incorrect answer to the first section. The final section of each question asks how confident the student is that their answer is correct.

All 11 students completed the EPSE test before and after the lesson sequence. All tests were marked after the lesson sequence. If a student answered the first section incorrectly, the explanation section was used to categorise the mistake as either an M2, M8, M9 or uncategorizable mistake using an answer key produced by the author of this report. In all cases, it was possible to categorize mistakes as one of the three misconceptions. It is important that researchers investigating conceptual understanding should not 'teach-to-the-test', obscuring a lack of conceptual understanding in areas not covered by the test (Taber, 2007; Robson & McCartan, 2011). However, as elimination of misconceptions through conceptual change activities was an important teaching goal, addressing the three misconceptions was unavoidable.

DIRECT questions

The Determining and Interpreting Resistive Electric Circuit Concepts Test (DIRECT) was developed in response to the desire for a conceptual test like the Force Concept Inventory (FCI) for the topic of electric circuits (Engelhardt, 1997). Two versions of the test are commonly used: v1.0 which uses qualitative questions, and v1.2 which was updated to include more mathematical questions in response to the difficulty students had with v1.0. Engelhardt notes that "Version 1.2 is most appropriate for an emphasis on the quantitative aspects of circuits, whereas 1.0 is more suited for a qualitative approach." (Engelhardt & Beichner, 2004, p.110). As quantitative questions have been shown to be a poor indicator of conceptual understanding, v1.0 was used (Millar & Beh, 1993; Crouch & Mazur, 2001; McDermott, 2011). The test contains 29 multiple choice questions (see Figure 3).

While there was not time to administer the full test to the class, the questions from the test were used both to encourage qualitative reasoning and to assess student understanding. Students answered two questions at the beginning of each lesson and then answered the same two questions at the end of the lesson to assess how their understanding had progressed. Students were encouraged to describe their reasoning below their answer, so it was possible to see how their reasoning skills had developed. However, comparisons must be made cautiously as it was possible students may have discussed the question with peers before re-answering the question at the end of each lesson, though no indication of this was seen. Students were told there would be no positive or negative consequence to their answers, and that the questions were intended only to provide practise and evaluate teaching. Students were also asked how confident they were their answers were correct, using the same scale as the EPSE test.

This test has been used in several other studies, allowing for comparison of results by question with typical results from 1135 high-school and university students (Engelhardt & Beichner, 2004). However, as students completed the questions two at a time during a lesson related to the questions, and not as a full test, comparisons are not completely valid.

Focus groups

Focus groups with students were used to attain a more detailed picture of how and why students' conceptual understanding, attitudes and confidence had changed as a result of the lesson sequence. The CLASS survey was used to select two students whose attitudes towards physics had become more-expert-like in both the 'Overall' and 'Applied Conceptual Understanding' categories, as well as two students whose attitude had become less expert-like in these areas. These two pairs of students agreed to take part in the two focus groups.

To avoid the potential for bias introduced by asking questions about the effectiveness of the interviewer's own teaching (Bell, 2010; Robson & McCartan, 2011), a structured interview format was used. Students were asked to explain their answers to selected questions on the CLASS survey and EPSE test, and to explain "if there was any reason why your views changed between the pre-test and post-test". The focus groups were audio-recorded and then transcribed. The transcripts were used only to support judgements suggested by other data, as the small sample-size of the interviews makes generalisations impossible.

Research Question	Data source			
	CLASS surveys	EPSE tests	DIRECT questions	Focus groups
1. Do pedagogies which emphasise qualitative reasoning improve students' conceptual understanding of electric circuits?		✓	✓	✓
2. How do pedagogies which emphasise qualitative reasoning affect students' attitudes towards physics as a subject?	✓			✓
3. How do pedagogies which emphasise qualitative reasoning affect students' problem-solving confidence in physics?	✓	✓	✓	✓

Table 2: Data sources used in addressing each research question

Discussion

Do pedagogies which emphasise qualitative reasoning improve students' conceptual understanding of electric circuits?

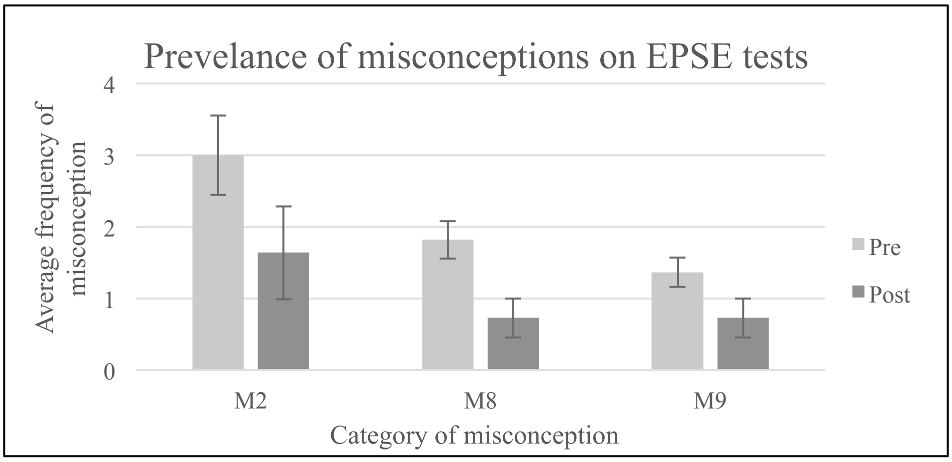

***Figure 4: The average number of incorrect answers given by each student in the EPSE test due to the three identified misconceptions (see above)**

**Note: comparisons between the prevalence of the three misconceptions should be avoided as there were not an equal number of opportunities to make mistakes due to each misconception.*

Results from the pre- and post- EPSE test indicate a significant decrease in the prevalence of misconceptions after the lesson sequence (see Figure 4). However, as no control group was used it is not certain whether similar gains would be observed under typical quantitative instruction. While the prevalence of misconceptions is not the only indicator of conceptual understanding, several other studies have focused on the prevalence of misconceptions to determine the effect of pedagogies on conceptual understanding. Investigations into the effect of qualitative questioning (Leonard et al., 1996; Crouch & Mazur, 2001), inquiry-based model-building (Afra et al., 2009) and conceptual change instruction (Taşlıdere, 2013; Dilber & Salar, 2014) have all found decreases in the prevalence of misconceptions on similar electric circuits conceptual tests. In one study a control group was taught using typical quantitative questioning, and the prevalence of misconceptions was shown to increase (Taşlıdere, 2013). Indeed, the prevalence of some misconceptions, particularly M8 (the power supply as constant current source), have been shown to be approximately constant at all stages of physics education (Engelhardt & Beichner, 2004). Therefore, the decrease in misconceptions on the EPSE tests is a strong indicator that conceptual understanding was improved by the pedagogies which emphasise qualitative reasoning.

Another indicator of the improvement in conceptual understanding is the increase in student performance on DIRECT questions between the beginning and end of each lesson (see Figure 5). The class typically performed worse than the standard results at the beginning of the lesson, but performed better at the end of each lesson. While performance on each question increased due to the lesson, this may be because lessons covered the topic in the corresponding question, so comparisons with results of other students taking the whole test are not entirely valid. However, an increase in performance on DIRECT questions has also been observed in similar secondary school studies on the impact of inquiry-based model-building (Afra et al., 2009) and conceptual change instruction (Kapartzianis & Kriek, 2014). Comparison with these similar, although small-scale, studies strengthens the argument that the combination of pedagogies which emphasise qualitative reasoning caused both the increase in DIRECT question performance and the decrease in the prevalence of misconceptions on the EPSE test.

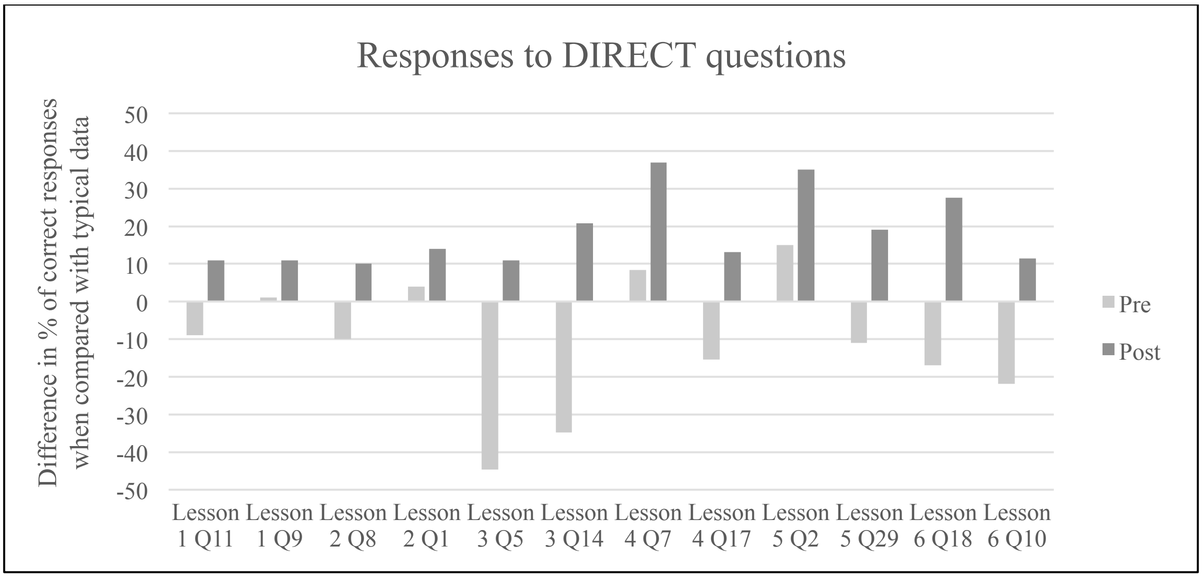

Figure 5: Student responses to DIRECT questions

The percentage of correct responses given by the class is compared with typical results from 1135 high-school and university students answering the same questions (Engelhardt & Beichner, 2004)

Students' written reasoning on DIRECT questions shows the ways in which students' reasoning skills increased due to instruction. Take the question in Figure 3 for example. At the beginning of lesson 3, three students' responses were "C. Resistance in circuits is added", "C. There are the same number of resistors" and "B. In series resistance adds up and increases whereas in parallel the total resistance is reduced". While the last student does give the correct answer, all resort to memorized mathematical rules to explain their thinking, as has been observed in studies of students of similar ages studying electric circuits (Cohen et al., 1982; Millar & Beh, 1993). Two students hold an M9-type misconception, focusing on the number of resistors, rather than their arrangement (Taşlıdere, 2013). By the end of the lesson, all three students gave correct answers with appropriate conceptual reasoning: "B. There is only one pathway for electrons in the first one", "B. The current had more ways to flow so resistance is reduced" and "B. The parallel section provides another channel which decreases the total resistance". This trend of movement from quantitative to qualitative reasoning was typical of DIRECT question responses. One student when interviewed described how "At the start I was trying to relate it to the equation, but it's different because the current goes through two pathways. I thought it was related to the equation but no, it just pulls more current through" (Student B, Focus group 1). Another said "Before we did the circuits I never actually like looked at what it is… we never did experiments that actually visualise the circuit. Now when I think about it I visualise it and try to simplify and work through it" (Student A, Focus group 1). This may suggest that the emphasis on qualitative reasoning encouraged students to think about conceptual models, rather than resorting to memorized algorithms which may lead them astray. While qualitative reasoning improved, failure to distinguish among related concepts was still a common mistake (McDermott & Schaffer, 1992a). One student was able to answer an EPSE question correctly, but still made the common mistake of confusing current and voltage (Millar & Beh, 1993). In interview, they described how in a parallel circuit "The voltage splits here so half the volts go here and half here" (Student B, Focus group 2). As has been previously documented in an undergraduate study (Leonard et al., 1996), students were resistant to the use of "strategy" and "solution" writing frames, which many, but not all, ignored.

There is some evidence to suggest that conceptual change discussions were the most important factor in improving students' conceptual understanding. When asked why their answers changed between pre- and post- EPSE tests, all four students interviewed referred to conceptual change discussions at the beginning of lessons. The two lessons without conceptual change discussion also gave the smallest gain in DIRECT question performance (see Figure 5). This suggests that the "elicit, confront, resolve" model of conceptual change was an effective way of improving conceptual understanding, as found in two other studies of 16-18 year old students studying electric circuits (Dilber & Salar, 2014; Kapartzianis & Kriek, 2014). However, conceptual change activities were not always effective in changing students' ideas. Students sometimes defended their misconceptions against sensory evidence, and would deliberately record unobserved results, a behaviour which has been observed in a study of younger 11-12 year old students (Arnold & Millar, 1987). For example, one student who believed that the brightness of one bulb must be affected by the connection of another bulb in parallel repeatedly claimed that the bulb must get slightly dimmer, but that it is so slight it cannot be seen. Further studies of conceptual change discussions which determine their isolated effect and produce guidance to avoid potential pitfalls may be beneficial.

How do pedagogies which emphasise qualitative reasoning affect students' attitudes towards physics as a subject?

There is little evidence to indicate that student's attitudes towards physics were significantly changed as a result of the lesson sequence. No significant shift in overall favourability of students' views was observed (see Figure 6). Despite the emphasis placed on conceptual understanding, no significant shift was seen in the 'Applied Conceptual Understanding' category. This may be expected, as the interval between the pre- and post-test was only 4 weeks, a small period of time in which to change students' views of a subject they have studied for several years.

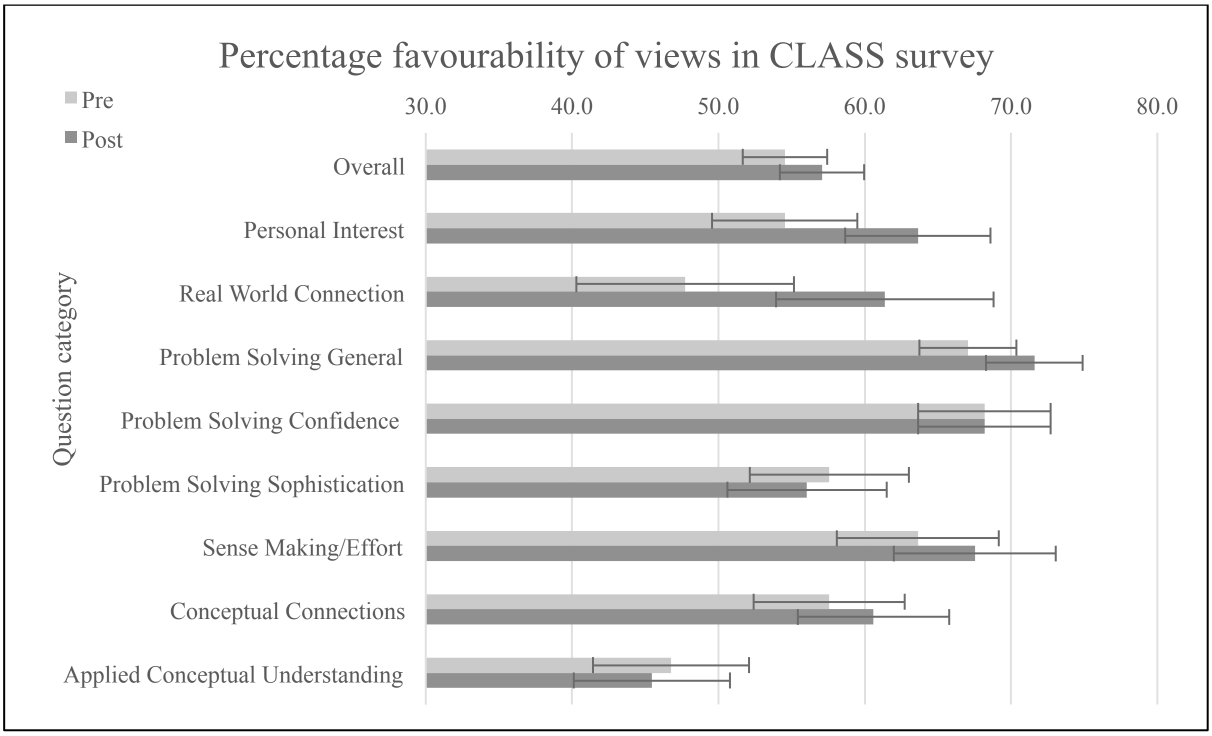

Figure 6: The percentage of favourable views students gave in the CLASS survey before and after the lesson sequence

There is some evidence that pedagogies which emphasise qualitative reasoning had a positive effect on student views, particularly when compared with typical changes in student views. Students' views about physics usually become less expert-like following instruction, though this has only been observed at undergraduate level (Redish et al., 1998; Adams et al., 2006; Ding, 2012). No negative shift in favourability was observed in any category, though this may be due to the short duration of the lesson sequence. Significant positive shifts were observed in the 'Personal interest', 'Real World Connection' and 'Problem Solving General' categories. One student said in interview:

> "I had an understanding of how voltage and resistance work, but this year it's become clearer as to what it actually is. As opposed to just saying voltage is a push on the current, it's how it actually forces a current to go around, how it pushes electrons around. It just feels like learning more and understanding better. It's like I can apply it more to real life than I could before."
>
> (Student A, Focus group 1)

For this student, an increase in conceptual understanding has made it easier for them to apply physics to real life, which may explain the positive shift in the 'Personal interest' and 'Real World Connection' categories. If given more time to investigate pedagogies which emphasise qualitative reasoning, it would be interesting to see whether a positive shift in overall views would be observed, as in other studies which "emphasized reasoning development [and] model building" (McKagan et al., 2006, p.1; Brewe, et al., 2008; Sahin, 2010; Lindsey et al., 2012). However, these studies were all of undergraduate students, who may encounter these pedagogies less frequently in lecture-based courses and therefore the introduction of these pedagogies may cause a greater shift in views.

Several studies note a correlation between expert-like views and improvement in performance on conceptual tests, suggesting that those with expert-like views are more likely to improve their conceptual understanding. (Perkins, Adams, Pollock, Finkelstein, & Wieman, 2004; Sahin, 2010; Milner-Bolotin, Antimirova, Noack, & Petrov, 2011). However, no significant correlation between improvement in EPSE test performance and favourability of views on the CLASS survey was observed.

How do pedagogies which emphasise qualitative reasoning affect students' problem-solving confidence in physics?

Unlike another study which implemented the Physics by Inquiry curriculum in an undergraduate context (Lindsey et al., 2012), no shift was observed in the 'Problem Solving Confidence' category of the CLASS survey. This disparity may be due to the short duration of the lesson sequence or the differing experiences of secondary-school and undergraduate students. Students' confidence in their answers on EPSE tests and DIRECT questions increased due to instruction (see Figures 7 and 8). However, as no control group was used, it is difficult to determine whether increases in confidence were due to pedagogies which emphasise qualitative reasoning, or simply due to more exposure to the topic of electric circuits.

There is some concern that conceptual change instruction focusing on eliciting misconceptions may cause a loss of confidence, particularly among low-achieving students. This was observed in a study of 219 16-year old students in Israeli secondary schools (Dreyfus et al., 1990). However, no statistically significant correlation between predicted grade and confidence shift was observed on EPSE, DIRECT or CLASS tests. However, the small sample size of this study may obscure this effect.

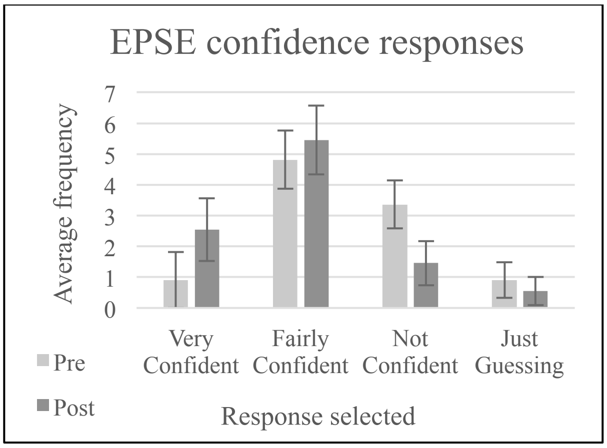

Figure 7: Average student confidence in EPSE tests before and after the lesson sequence

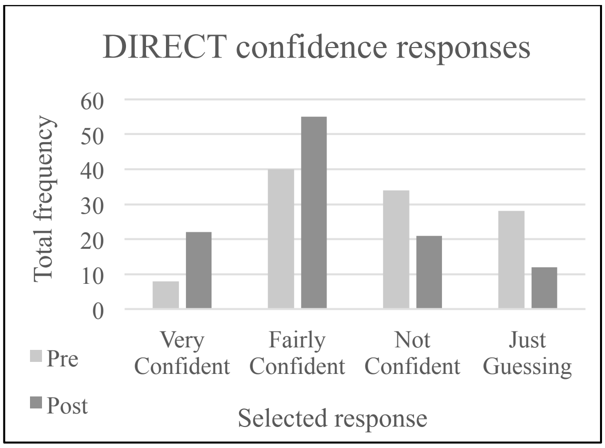

Figure 8: Total number of selections for each confidence response for DIRECT questions

Conclusion

There is evidence to suggest that the combined use of pedagogies which emphasise qualitative reasoning increased students' conceptual understanding of electric circuits. The prevalence of common misconceptions was found to decrease significantly between pre- and post-tests, a result that does not usually arise from typical quantitative instruction (Engelhardt & Beichner, 2004; Taşlıdere, 2013). Performance on conceptual DIRECT questions also increased. Pedagogies which emphasise qualitative reasoning had very little measurable effect on students' attitudes towards physics and problem-solving confidence, likely due to the brevity of the study. Positive attitudinal shifts were observed in the categories of 'Personal interest', 'Real World Connection' and 'Problem Solving General', and no decrease in 'Problem Solving Confidence' was recorded, despite suggestions that conceptual change activities may results in a loss of confidence (Dreyfus et al., 1990).

Implications for practice

The use of conceptual change discussions using the model of "elicit, confront, resolve" was identified by students as a particularly effective method of improving conceptual understanding, as has been shown by several other studies at undergraduate (McDermott & Shaffer, 1992b, p.1008; Sangnam & Jesiek, 2012; Taşlıdere, 2013) and secondary school level (Arnold & Millar, 1987; Dilber & Salar, 2014; Kapartzianis & Kriek, 2014). This is a method which has been shown to be effective in eliminating misconceptions not just for electric circuits, but all of science (Posner et al., 1982; Dreyfus et al., 1990).

The positive effect on conceptual understanding of the use of qualitative questions has been well established in an undergraduate context (Arons, 1982; Cohen et al., 1982; Crouch & Mazur, 2001; Gaigher et al., 2007), but few studies have documented this effect in secondary schools. A transition from quantitative to qualitative explanations for phenomena was observed in students' work. This study supports the conclusion of another secondary school study that encouraging students to take qualitative reasoning in physics seriously is likely to lead to increases in conceptual understanding and reasoning skills (Gaigher et al., 2007). This has increased my determination to use qualitative questions and teaching strategies to support students in my own teaching.

Opportunities for future research

The study was severely limited in several facets. Only part of the AS-Level electricity curriculum was taught using the pedagogies described above, and no control group was used. A long-term study implementing the described pedagogies with a control group may yield more significant results.

The lesson sequence had little effect on students' views about physics, however views did become more favourable in the 'Personal Interest', 'Real World Connection' and 'Problem Solving General' categories. It would be interesting to see if, in a long-term study, a shift in overall views would be observed, as in other studies of undergraduate students (McKagan et al., 2006; Sahin, 2010; Lindsey et al., 2012).

As this study takes the form of action research, which is typically a cyclical process (Denscombe, 2007), another opportunity for further research would be to refine the pedagogical techniques and observe their effect. Improvements could be made in encouraging the use of 'strategy' and 'solution' writing frames, as well as overcoming the identified pitfall in conceptual change activities: students' denial of sensory evidence (Arnold & Millar, 1987).

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