A study of the conceptual comprehension of electric circuits that engineer freshmen display

Wheijen Chang\(^1\) and Ruey S Shieh\(^2\)

\(^1\)Department of Physics, National Changhua University of Education, Changhua, Taiwan
\(^2\)Department of Information Management, Kainan University, Taoyuan, Taiwan

E-mail: ruey99@gmail.com

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Abstract

The purpose of this study was to examine the extent of students’ conceptual comprehension of electric circuits obtained during their high school years, as opposed to in recent class lectures. A total of 201 first-year university students majoring in Engineering in four introductory physics classes were involved in the study. A lecture demonstration of electric circuits was designed to achieve the study purpose. After observing the demonstration, the students were required to identify the associated phenomena and then explain the underlying physical laws. The students’ reasoning performance was used to examine their conceptual comprehension. Two instructional strategies, group discussion without prior lecture and individual reasoning with prior lecture, were implemented to assess student performance. The findings disclosed that although the students had studied the topic previously, most of them could only identify the key phenomena involving simple principles, but failed to identify those involving profound ones. The models most of them adopted were scientifically acceptable but inappropriate in the given context. The students who engaged in group discussion appeared to have a higher phenomenon identification rate than that of the individual-reasoning group. Contrarily, the individual-reasoning group was found to have adopted the valid principles more effectively than the discussion group, probably due to the prior instruction received in the current class. The topics recently lectured seemed to have guided the students’ cognitive orientations toward selecting...
principles, regardless of their validity. The study findings reveal that the concepts the students had acquired from their earlier learning were rather limited. That is, sophisticated instructional design is always pivotal, regardless of students’ prior learning experiences. Moreover, when adopting demonstration as a teaching tool, explicit instructional guidance is also crucial.

Keywords: electric circuits, demonstration, conceptual comprehension

(Some figures may appear in colour only in the online journal)

Introduction

Physics is difficult for learners when it involves learning abstract and profound concepts, even if the same topics have been studied multiple times, such as electric circuits and Newton’s laws of motion. In Taiwan, most students, however, regard electric circuits as a relatively easy topic, as the physics concepts involved are simpler and the mathematical skills required are also easier, especially compared with the topics of electrostatics and magnetism. Students in Taiwan initially learn the electric circuit topic in their secondary school years. In college, those whose major is associated with the science and engineering fields will learn it again. Nonetheless, it is reported that the majority of Taiwanese teachers are prone to use the traditional one-way lecture method to teach physics courses, and mainly focus on mathematical formula practice (Chang 2005). Many researchers (e.g. Lee and Law 2001, Mestre 2001, Reif 2008) have contended that teaching introductory physics using the traditional lectured approach might not effectively help students acquire conceptual understanding. Therefore, whether the students who had passively learnt the subject thoroughly comprehend the principles taught is of concern. This motivated us to examine to what extent the university freshmen who had learnt the subject previously had grasped the electric circuit concepts.

In Taiwan, the following laws related to electric circuits are covered in the senior high school physics curriculum: (1) Ohm’s law, (2) resultant resistance of circuit assemblies, (3) equations of electric power \( P \) as a function of electric current \( I \), resistance \( R \) and potential \( V \) \( P = IV = I^2R = V^2/R \), and (4) resistance \( R \) of metal resistors depending on temperature \( T \) \( R(T) \). Although physics textbooks provide abundant exercises and end-of-chapter problems for students to practice the integration of the physical laws of (1)–(3), there is a lack of examples regarding how the 4th law \( R(T) \) is related to the laws of (1)–(3). Most of the provided exercises related to the law of \( R(T) \) are limited to calculating the resistance variation of single resistors, instead of evaluating current \( I \), voltage \( V \), and power \( P \) of circuits containing multiple resistors. In other words, the empirical law of \( R(T) \) is often introduced and practiced independently from the other three. Due to the missing link, students are likely to encounter difficulties combining the four laws. Therefore, it was also the intention of this study to assess the students’ reasoning ability of integrating the 4th physical law \( R(T) \) into the first three laws through a lecture demonstration. In addition to showing a purposefully selected demonstration, two instructional strategies, individual reasoning with prior lecture as opposed to group discussion without prior lecture, were implemented to examine the students’ conceptual reasoning performance. Two research questions guided this study:

1. What is the student performance of conceptual comprehension in electric circuits, particularly for the empirical law of \( R(T) \) and its links with Ohm’s law, circuit assembly, and equations of electric power, after having acquired prior knowledge from their secondary schooling?
2. Do different instructional strategies affect students’ conceptual reasoning performance?
Literature review

Using demonstration as instructional guidance

Showing demonstrations in science classrooms may help students encounter cognitive conflict, whereby they become dissatisfied with their prior conceptions, thus triggering a shift from their naïve ideas to scientific models (Duit and Treagust 1998). However, some instructors adopt demonstrations simply as a tool to liven up their classrooms (Di Stefano 1996). Consequently, students may regard lecture demonstrations as appealing but irrelevant to their ‘official’ learning tasks (Gunstone and White 1981). In terms of epistemological consideration, superficial epistemological beliefs may influence students’ motivational orientation and prevent their conceptual learning (Pintrich et al 1993). Crouch et al (2004) contended that in-class demonstration should play the role of neither entertainment nor mediation in direct instruction. Rather, it should be utilised as a tool for engaging students’ thinking and discussion, and then for facilitating their conceptual understanding (Sokoloff and Thornton 1997). Some researchers have warned that conceptual learning through watching demonstrations must be designed subtly in order to achieve the instructional objectives (Shepardson et al 1994) or students may completely ignore the key phenomena that the teacher is attempting to illustrate in the demonstration (Roth et al 1997). They may instead tend to observe (a) what they have predicted (Gunstone and White 1981), (b) the associated principles they have recently learnt (Roth et al 1997), and/or (c) the underlying conceptions they have comprehended (Miller et al 2013). Crouch et al indicated that allowing students to make predictions helps them to observe the phenomena that the instructor intends to present. Some scholars have further asserted that even if students have noticed the correct phenomena, they may be prone to explaining the observed situations with intuition rather than with appropriate scientific models if they lack the basic knowledge of the related principles (Miller et al 2013). Hammer (1996) claimed that utilising demonstration to conduct conceptual reasoning is more challenging than many teachers may think. The researcher contended that difficulties students encounter may be related to their misconceptions and also their beliefs about physics knowledge existing independently. Subsequently, they may tend to use a single law, rather than integrating multiple laws, when explaining real-life examples.

Scientific conceptual reasoning

When engaging in reasoning science, Driver et al (1985) summarised several pitfalls which students are prone to fall into, including (1) perceptually dominated thinking, (2) limited focus, and (3) undifferentiated concepts. As for perceptually dominated thinking, students tend to reason based on sensible phenomena. For example, they think that light exists only on a patch of surface rather than travelling through space. Based on a social constructivist view, scientific conceptions are specifically defined by scientists, the meanings and usages of which may be novel or discrepant to those adopted in daily life experiences (Airey and Linder 2009). Scientific terminologies such as light or electric current are defined by the scientific community rather than being directly sensible; thus, scientific models may not be easily perceived. Larkin (1983) noted that ‘a physical representation’ (p 78), such as energy, contains fictitious entities; thus, they need to be thoroughly defined and depicted. Meanwhile, learners may also limit their focus during observation; they may only notice the obvious changing features of individual items, rather than considering the interaction between the elements of a system (Driver et al 1994). In addition, students may also commit to undifferentiated concepts and
apply one notion to several physical quantities. For example, when defining insulators, they may refer to both ‘rate of heat transfer’ (power) and ‘ability to hold warmth or coldness’ (temperature variation). In electric circuits, students were found to believe that the electric current may be ‘consumed’ along a series of resistors, which implies their confusion between electric energy and current (Engelhardt and Beichner 2004). Therefore, it is important that the instructor assists students to avoid the superficial cognitive tendency addressed above. In order to help students avoid superficial reasoning habits and adopt sophisticated scientific models, students need to be aware of the discrepancy among similar terminologies and be able to logically connect related principles. However, Koupilová et al (2017) contended that most of the problems and their solutions provided by conventional learning materials are insufficient for students to undertake active learning, such as hints (to shape the problems), verbal analysis, and comments of alternative solutions. To achieve the pedagogical goal, some researchers have emphasised the importance of devising well-designed instructional sequences which aim at providing comprehensive guidance and effectively engaging students’ thinking (e.g. Méheut and Psillos 2004).

To enhance students’ capability of conceptual reasoning, it is necessary that the related scientific principles be integrated. Di Stefano (1996) argued that physics content is usually presented as discrete pieces, rather than as a coherent picture linking concepts. For example, Newton’s Laws of Motion are often introduced separately without showing the connections among them (Physics Textbook Review Committee 1998). Buncick et al (2001) suggested that examples used for lecture demonstration comprise multiple principles and provide an opportunity for students to integrate the related ideas and strengthen their conceptual framework. Chabay and Sherwood (2006) suggested linking the abstract field concepts of microscopic perspectives to reason the macroscopic variables in electric circuits in order to make the concepts of electric current and potential differences more comprehensible.

Misconceptions related to electric circuits

It is not uncommon for students to persistently possess a variety of naïve ideas (misconceptions) when learning physics. For example, students usually think that an electric current takes time to gradually flow through the resistors from the battery (temporal delay), and that the same battery (the pump) ‘transmits’ a fixed amount of current (water), regardless of the resistance of the circuits (Engelhardt and Beichner 2004). Similarly, they tend to believe that the magnitude of the current is only influenced by the elements as they are encountered; thus, the variation of the latter resistors does not influence the current of the prior resistors (Shipstone 1984). Even secondary teachers have been found to reason the brightness of electric bulbs based on electric current only; thus, the same electric current leads to the same brightness regardless of the difference in resistance (Wong et al 2017).

When teaching electric circuits, incandescent lamps (bulbs) are usually utilised as equipment to illustrate the associated physical principles. The illumination of bulbs obey Stefan–Boltzmann’s law: radiation spectra depend on their temperatures. Radiation lights become visible when objects are heated to 850 K (red light). The temperature of the tungsten filament of bulbs is about 2800 K (Denardo 2002), which emits only 10% within the visible light region while 90% radiates at infrared wavelength. In order to maximise the efficacy of illumination, the filaments are wound into an intricate coil at the scale of $10^7 \mu m$ due to the maximised surface area of the lightbulb filaments; the brightness of the electric bulbs depends on the exhausted electric power rather than the accumulated electric energy (MacIsaac
et al 1999). Because of the wide range of temperature variation of operating bulb filaments, the temperature dependence of the resistance is significant. The resistance of a 60 W bulb increases from 16 $\Omega$ at room temperature to 240 $\Omega$ at operating temperature (2800 K), which is a difference of 15 times (Denardo 2002). Therefore, incandescent bulbs serve as a suitable context to adopt the empirical law of temperature dependence of resistance; however, this theory was found to be prevalently overlooked by not only students but also physics teachers (Wong et al 2017).

The instructional strategies

It is important that learners be provided with opportunities to construct their own knowledge, which is seen to be more effective than traditional didactic lectures during their learning process (e.g. Lee and Law 2001, Mestre 2001, Reif 2008). The teacher’s role is mainly to provoke students to think, reason, and link the contexts taught to their existing knowledge (Windschitl 2002). While personal constructivism emphasises learning through individual reasoning, social constructivism asserts that knowledge is constructed by group discussion (Marin et al 2000). Students may confront a series of difficulties when solving problems, such as being unable to differentiate similar terminologies; the transient learning challenges can be addressed by instant peer interaction or instructional guidance (Fredlund et al 2015). Several large-scale studies investigating students’ performance in standardised concept tests of tertiary introductory physics courses have found that the students assigned to the interactive teaching methods, such as group discussion, outperformed their counterparts in the traditional classes (e.g. Hake 1998, Thornton et al 2009). Meltzer and Thornton (2012) also disclosed that various teaching strategies, such as adoption of classroom response systems and peer instruction, which aim at promoting active learning, are beneficial to students’ conceptual development. In addition, some researchers have reported that the pedagogical benefits of adopting research-based instructional strategies not only aid cognitive development, but also promote motivation and retention of learning (Deslauriers et al 2011). However, Baviskar et al (2009) cautioned that group discussion may or may not be an effective teaching strategy, mainly depending on the thoroughness of the implementation.

Methodology

The teaching design

Demonstration equipment initiated by Greene (2002), called ‘lightbulbs with memory,’ was adopted to examine students’ conceptual comprehension of electric circuits, particularly their ability to integrate the empirical law of temperature dependence of resistance with other associated physical laws. A similar setup and a detailed explanation of the observable phenomenon of the gradual illumination of lightbulbs can also be found in Piskac (2006). In this study, the demonstration equipment was assembled using five identical electric bulbs connected in-series, and the joints between neighbouring bulbs were exposed to allow closed circuits with gradually increasing numbers of bulbs. Figure 1 shows the circuit diagram of the demonstration.

The demonstration conducted consists of the following two steps:

1. The instructor displays an electric circuit connected with five bulbs in a row, as shown in figure 2.
The instructor uses an iron stick to touch the connection between the first two bulbs from the front left, pauses for a few seconds, and then shifts to touch the connection on the right until the last one is touched. It is visible that once a certain connection is touched, the bulbs on the left will light up immediately, but the last bulb touched will gradually light up and will not reach stable brightness until one to two seconds later.

It should be noted that the students were not aware of the black-box part of the demonstration (i.e. figure 1 diagram); they were only informed that the five bulbs were identical before the instructor silently showed the demonstration. In other words, they were required to figure out the circuit assembly by themselves, as explained in the following ‘Brightness differences’ section below. After the demonstration, the students were asked to answer the following two questions:

1. What are the two phenomena they had observed?
2. What are the associated physical laws to explain each of the observed phenomena?

Two major phenomena are involved in the demonstration, and the related physical laws are described below.

1. Brightness differences

   Each of the bulbs becomes dimmer as more lightbulbs are connected (illuminated). For example, the bulbs shown in figure 3(a) (three bulbs lit up) are brighter than those in figure 3(b) (five bulbs lit up).

   The physics principle involved is that, since the lightbulbs are connected in series, the more lightbulbs that are connected, the higher the resultant resistance is, and the lower the current becomes, causing dimmer illumination (power) of the bulbs. To explain this phenomenon, students need to combine (1) Ohm’s law, (2) resultant resistance of in-series assembly, and (3) equation of electric power.

2. Temporal delay of lighting
Temporal delay of lighting occurs when touching the connection of the bulbs consecutively. That is, the illumination of the last connected bulb will increase gradually, rather than immediately, and it takes a short while for the bulb to reach a stable brightness, as shown in figure 4(b) versus figure 4(a). Figure 4(a) denotes that the right (latter) bulb was not lit up at the moment of just touching the right end, but after holding the iron stick for a few seconds, the latter bulb lit up, as shown in figure 4(b). According to Piskac (2006), the explanation requires integration of three principles: (1) since the front bulbs have already been heated, resistance ($R$) of the filaments increases when the temperature ($T$) is increased ($T \uparrow \Rightarrow R \uparrow$), thus the latter lightbulbs have lower resistance than the prior ones; (2) because the five bulbs are assembled in-series, they have equal electric currents ($I$) regardless of their resistance difference; (3) the brightness of the bulbs depends on their electric power ($P$), from $P = I^2R$, for equal current, electric bulbs with lower resistance use less electric power. Therefore, the latter bulbs take time to gradually heat up, and then gradually increase their resistance and increase the electric power accordingly.

The above phenomenon can be described more quantitatively using heat conduction in solids and temperature characteristics of resistivity of the lightbulb filament (Kraftmakher 2004) However, the students were required to qualitatively reason about the phenomena
they observed by means of macroscopic physical laws, rather than numerically manipulating quantitative models and equations.

**The participants**

A total of 201 first-year university students in four classes majoring in Engineering were involved in this study. The number of students in the four classes were 46, 52, 49, and 54, respectively. The course studied was entitled Introductory Physics. To distinguish the students’ comprehension level held from their secondary schooling from that acquired during the current class lecture, two types of instructional strategies were implemented: (1) group discussion without prior lecture, and (2) individual reasoning with prior lecture. The former was to examine whether group work helped the students refresh their conceptual knowledge obtained from high school, whereas the latter was to investigate the effect of the class lectures. Among the four classes, two were assigned to the group-discussion condition (labelled as G1 and G2), in which the students were required to observe the demonstration and then explain the phenomena via group discussion before receiving the instructor’s lecture. A total of 30 groups were formed, with three to four students in each. Each group was required to hand in one set of answers after reaching a consensus regarding the two questions raised by the instructor. In contrast, the other two classes assigned to the individual-reasoning condition (labelled as I1 and I2) were engaged in reasoning individually after listening to the instructor’s lecture on the laws of electric circuits. Specifically, they were taught about the four physical laws mentioned above and they also practiced two real-life examples. Although how the students learned the topics in their secondary school years was unknown, in this study the emphasis of practicing real-life examples could hopefully better help them connect the theories to their daily life situations. The time given for answering the demonstrated questions was the same for the four classes—approximately 20–25 min. Table 1 lists the number of students in the two conditions.

According to the evaluation of the University Entrance Examination, the average physics scores of the four classes (cohorts) were at the percentile ranks of 58% (I1), 59% (I2), 67% (G1), and 61% (G2). These rankings indicate that the G1 and G2 classes had a somewhat but insignificantly stronger academic background than the I1 and I2 classes in the physics subject.

**Data analysis**

Content analysis was used to analyse the students’ reasoning statements. It is anticipated that it would be relatively easier for the students to identify the first phenomenon than the second one as the former involves combinations of familiar laws, whereas the latter requires utilising relatively unfamiliar links among laws. Under such circumstances, the focus of the analysis would be on the second phenomenon identification and the provided reasoning statements. The data analysis of the second phenomenon includes: (1) whether or not the students were

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**Table 1. The number of students in the two instructional conditions.**

| Instructional conditions | Individual reasoning | Group discussion |
|-------------------------|----------------------|-----------------|
| Class                   | I1       | I2       | G1       | G2       |
| # of students           | 46       | 52       | 49       | 54       |
| # of groups             | n/a      | n/a      | 15       | 15       |
able to identify the temporal delay of the illumination, and (2) whether and how the students provided valid explanations for the phenomenon.

The students’ reasoning was coded into four categories: (A) valid, (B) scientific but ineffective, (C) naïve, and (D) meaningless. Definitions of these categories are listed in table 2. The ‘valid’ category indicates that the students adopted the valid (correct) scientific models. ‘Scientific but ineffective’ means that the students’ explanations actually fulfilled scientific definitions but the models adopted were ineffective in terms of explaining the given phenomenon. ‘Naïve’ basically reflects prevalent misconceptions addressed in the literature. Although the ‘naïve’ and ‘scientific but ineffective’ models are both incorrect, the two categories are associated with different learning demands. Examples of various learning demands are described below in the Results section.

To ensure reliability, the first author and one other physics instructor coded the students’ reasoning statements independently. Initially 88% of the overall consistency was obtained; however, the discrepancy was further discussed to reach full agreement.

### Results

**Comparing learning outcomes for two instructional strategies-phenomenon 1**

As expected, identifying and reasoning the first phenomenon (brightness differences) appeared to be easier than doing so for the second one (temporal delay of the lighting). The percentages of students who were able to identify the first phenomenon and also provide valid explanations are listed by class in table 3.

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**Table 2. Definition of the reasoning categories.**

| Categories | Definition |
|------------|------------|
| A. Valid   | Valid scientific models and reasoning |
| B. Scientific but ineffective | Scientifically acceptable but ineffective reasoning in the context |
| C. Naïve   | Non-scientific models, namely misconceptions or naïve ideas |
| D. Meaningless | Meaningless explanations |

**Table 3. Student performance for Phenomenon 1.**

| Teaching strategies | Class (student/group #) | Phenomenon identified | Valid explanations |
|---------------------|-------------------------|-----------------------|--------------------|
| Individual reasoning| I1 (n = 46)              | 40 (87%)              | 38 (83%)           |
|                     | I2 (n = 52)              | 43 (83%)              | 42 (81%)           |
|                     | Total (n = 98)           | 83 (85%)              | 80 (82%)           |
| Group discussion    | G1 (15 groups)           | 14 (93%)              | 14 (93%)           |
|                     | G2 (15 groups)           | 13 (87%)              | 13 (87%)           |
|                     | Total (n = 30 groups)    | 27 (90%)              | 27 (90%)           |
| Chi-square test     |                         | p = 0.464             | p = 0.279          |

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Table 3 shows that the majority of the students (81%–93%) in the four classes were able to identify the first phenomenon and provide valid explanations; that is, they were able to integrate Ohm’s law, resultant resistance of in-series assembly, and equation of electric power. The students in the group discussion condition (G1 and G2) slightly outperformed their counterparts (I1 and I2); however, the differences were insignificant, $p = 0.464$ and $p = 0.279$, respectively; both are greater than 0.05 level.

Comparing learning outcomes for two instructional strategies—phenomenon 2

In contrast to the performance of Phenomenon 1, the students appeared to have encountered more difficulties addressing the second phenomenon (temporal delay illumination of the latter bulbs) question. The student performance in Phenomenon 2 was broken down by the four categories shown in table 2. Comparison of student performance between individual reasoning (I1 and I2) and group discussion (G1 and G2) is listed in table 4.

Table 4 discloses that a higher percentage of students in the group discussion condition (83%) than in the individual reasoning condition (69%) was able to identify the phenomenon. However, none (0%) of the groups in G1 and G2 provided valid explanations, whereas 8% of individual students in I1 and I2 were able to do so. It is likely that the lecture provided to the students before the demonstration helped some of them elicit the valid scientific models. One example of the valid explanations (Category A) is cited as follows.

Higher temperature makes $R$↑. Based on $P = I^2R$, when $I$ keeps equal, bigger $R$ results in higher $P$ (power). Since the temperature of #1 > that of #5, #5 becomes dimmer than #1. (By I1, #16)

The above excerpt was regarded as a valid explanation in that the student firstly stated the law of temperature dependence of resistance, selected an effective equation of electric power ($P = I^2R$), identified the equal current and resistance dependence of power, and then attributed the illumination difference between bulb #5 and #1 to the variables of electric power and temperature. It shows that not only the integration of multiple physical laws but also the inclusion of multiple representations, including words, equations, and symbols, were used to explain the phenomenon. However, most of the students adopted only a single law to explain the observed phenomenon in words without using any symbolic representations. Nonetheless, a higher percentage of students in the group discussion condition (10%) adopted naïve models than those in the individual reasoning condition (5%). A common naïve
conception (or misconception) presented by the students is that they attributed the temporal delay of lighting up to the later bulbs needing time for the electric current to flow from the front to the back lightbulbs (Category C). It is an idea which violates the scientific models. For example, one student stated:

*Connecting the five bulbs in series results in an increase in the total resistance; it becomes difficult for the electric current to flow across; therefore the latter lightbulbs light up slowly.* (By G2, #7)

In addition, some of the students were found to have provided scientifically acceptable arguments, but ones which were ineffective in explaining the observed phenomenon (Category B). A higher percentage of the group discussion students (47%) than the individual reasoning students (30%) provided responses pertaining to category B. Details of the ineffective scientific models adopted by the students are addressed in detail later. Meanwhile, the pitfall of adopting ineffective scientific models (Category B) was more common than that of holding misconceptions (Category C). In this aspect, it seems that group discussion is more helpful than individual reasoning in terms of provoking students’ reasoning endeavours, regardless of the accuracy of the answers. As for meaningless explanations (Category D), students in both conditions appeared to have similar performance, 26% versus 27%. An example of a meaningless explanation is provided as follows.

*The part which was connected would have residual circuit, so it shortened the time to light up the bulbs.* (By I2, #23)

### Types of ineffective scientific models

Since quite a few students in the four classes adopted models which were scientifically acceptable but ineffective in terms of explaining the phenomenon, the adopted models were thus further examined. The models are categorised into three types based on the following principles:

(a) Residual temperature: the prior bulbs may have residual temperature or may accumulate heat.

(b) Containing capacitors: the bulbs may contain capacitors which accumulate charges or electric energy once connected previously.

(c) Alternative circuit assembly: the five bulbs may be assembled both in-series and in-parallel.

Table 5 lists the numbers and percentages of the types adopted by the students, broken down by teaching strategy.

| Instructional conditions       | Classes   | (a) | (b)  | (c)  | Sum    |
|-------------------------------|-----------|-----|------|------|--------|
| Individual reasoning          | I1 + I2 (98) | 19 (19%) | 5 (5%) | 5 (5%) | 29 (30%) |
| Group discussion               | G1 + G2 (30) | 9 (30%) | 5 (17%) | 0 (0%) | 14 (47%) |

*a  (a) Residual temperature, (b) containing capacitors, (c) alternative circuits assembly.

*b  98 individuals.

*c  30 groups (103 individuals).
According to table 5, among the ineffective scientific models, relatively more students attributed the temporal delay of the lightbulbs to the residual temperature (Type a) or the capacitor (Type b) model. A few students in C1 and C2 utilised a combination of parallel and series circuit assembly of the five bulbs to explain the phenomenon (Type c). Examples of each type of ineffective scientific model are provided below.

Because lightbulbs need to reach a certain high temperature in order to illuminate, the prior bulbs have already been connected and are thus closer to the required illuminated temperature than the latter bulbs. (Residual temperature) (by G2, #14).

The circuit may contain charging devices like capacitors allowing the prior bulbs to accumulate higher voltages in order to illuminate faster. (Containing capacitors) (by G1, #3).

The filaments need to be super-hot in order to illuminate, so there must be a combination of in-series and in-parallel (among the five bulbs). (Alternative circuit assembly) (by I2, #50).

The residual temperature (or heat) model adopted by the students, as shown in the first citation, sounds plausible. However, since the filaments of the lightbulbs are composed of a considerable proportion of surface area, the consumed heat is almost equal to the supplied amount when connected. According to MacIsaac et al (1999), the key quantity to determine the brightness is not the accumulated energy but electric power. In other words, model (a) can be a valid explanation if the filament of the electric bulb is shaped by a significantly lower ratio of surface area to its volume than normal ones. Meanwhile, model (b) would also be valid if incandescent bulbs contain capacitors.

It was also found that it is likely that the students’ ineffective explanations could be associated with the topics the instructor lectured right before the experimental demonstration. Among the three types, more students in the group-discussion condition (G1 and G2) adopted the capacitor model (Type B) than the other two models because they had just finished studying that topic before the demonstration. In contrary, more students in the individual reasoning condition (I1 and I2) linked the observed phenomenon to circuit assembly combining in-series and in-parallel circuits (Type C) because the instructor had just lectured that topic prior to the demonstration.

Discussion

In addition to addressing the two research questions of this study (student performance of conceptual comprehension and impact of instructional strategies), one additional aspect regarding the students’ habits of conceptual reasoning is also discussed below.

Types of conceptions held by the students

The overall student performance of conceptual comprehension is discussed based on the types of conceptions held by them. It appears that the majority of the students (81%–93%) successfully identified and provided valid explanations (Category A as defined in table 2) in phenomenon 1 because it involved relatively familiar physical laws, including Ohm’s law, resultant resistance of in-series circuits, and equations of electric power. In contrast, no more than 8% of the students in the four classes provided Category A (valid) explanations in phenomenon 2 as it required the students to integrate the empirical law of temperature
dependence of resistance into some other laws. The analysis results disclose that the pitfalls the students encountered included (1) tending to notice only those phenomena for which the principles had been thoroughly comprehended, (2) adopting a single law in single-form (verbal) representation, (3) failing to differentiate similar physical quantities and ignoring more counterintuitive ones, such as utilising temperature or heat rather than power, and (4) evoking physics models which had recently been learnt.

The challenges that the students encountered were not only related to adopting naïve models (Category C), such as ‘currents take time to flow,’ as reported in Engelhardt and Beichner (2004), but also using ineffective but scientifically acceptable models (Category B). Even though some of the participants in this study were committed to possessing common misconceptions (i.e. using naïve models), they seemed to have struggled when selecting and integrating the associated physical laws as well. This indicates that simply initiating the learning task of overcoming misconceptions posed by personal constructivism (Lee and Law 2001, Zimrot and Ashkenazi 2007) may not be sufficient for the students to achieve conceptual comprehension. In other words, the pedagogical purposes of lecture demonstration should not be limited to showing anomalies or cultivating cognitive conflict to facilitate conceptual change, as addressed by Shepardson et al (1994).

It was also noticed that both groups of students tended to adopt ineffective scientific principles that they had just learnt, such as alternative circuit assembly and the capacitor model. It seems that the most recent learning experiences led to triggering their reasoning orientations, consistent with Roth et al’s (1997) contention. However, it is possible that the reason the students adopted ineffective but scientifically acceptable models could be attributed to the insufficient information regarding the demonstration process. Without receiving any hints about the black-box (i.e. the circuit assembly) to be observed, the students might have had trouble instantly linking the phenomena identified to the valid scientific models.

**Student performance between two instructional strategies**

When dealing with simple tasks, such as reasoning Phenomenon 1 in the current study, the instructional strategy of group discussion, as opposed to individual reasoning, was found to be able to help students come up with accurate answers. However, when coping with more complicated phenomena, such as reasoning Phenomenon 2 in the present case, group discussion was not as helpful. Nonetheless, the group discussion activity seemed to be beneficial for encouraging the students to commit to reasoning endeavours, coherent with Deslauriers et al’s (2011) study findings. Similarly, some other researchers have also contended that group discussion is beneficial (e.g. Meltzer and Thornton 2012), but it is not sufficient for facilitating valid conceptual reasoning, which depends on the complexity of the contexts, as asserted by Baviskar et al (2009).

With respect to reasoning Phenomenon 2, simply allowing students to engage in group discussion without providing any instructional guidance was ineffective, indicating that the students either had not acquired the associated physics knowledge or could not apply their prior knowledge to the current learning context. In such circumstances, it is not surprising that the individual-reasoning classes, after receiving instructors’ teaching at university, were better able to adopt more directly related principles than the group discussion classes, even though the former did not interact with their peers. In order to enhance learning effectiveness, instructional guidance is highly demanded, such as (1) providing hints to help identify the key phenomena, (2) informing the students of the components of the ‘black-box’ and the structure of the equipment (the bulbs), and (3) helping the students to differentiate similar terminologies and integrate well-known but apparently independent knowledge in a logical manner.
The demand of explicit instruction is in accordance with the notion of social constructivism regarding the socialised nature of physics knowledge, which is constructed and consented by the scientific community (Larkin 1983, Driver et al 1994, Airey and Linder 2009).

**Habits of conceptual reasoning**

Based on the analysis of the students’ explanations, some common habits of conceptual reasoning committed by the tertiary participants in this study were disclosed. First of all, the students tended to adopt intuitive terminologies but neglected abstract ones, such as using temperature or heat rather than electric power to explain the illumination of the electric bulbs. The findings show that the pitfall of undifferentiated concepts, as summarised by Driver et al (1985), is a common situation of naïve reasoning habits. Secondly, most of the students limited their explanations to verbal representation; not many of them utilised other forms of representations, such as symbols, equations, or diagrams. Larkin (1983) argued that different forms of representation can depict different features of science knowledge. The absence of using symbolic scientific representations may prevent students from effectively presenting their reasoning. As some social constructivism researchers (e.g. Airey and Linder 2009) have pointed out, scientific terminologies and some forms of representations may be counter-intuitive and abstract. Thus, repeated and instant instructional guidance and learning practice are crucial to help students gradually comprehend the meanings and usages of the scientific artifacts (Chang 2011, Fredlund et al 2015). Lastly, the students tended to adopt a single principle rather than integrate multiple principles as the context required. This habit (or epistemological belief) regarding physics principles as independent and discrete learning units may prevent students from combining several physical laws and thus enhancing their conceptual reasoning ability (Hammer 1996). Coherent with the literature, particularly Chabay and Sherwood (2006) and Di Stefano (1996), to reinforce students’ conceptual comprehension, teaching materials should strengthen the linkage among physics principles. In the meantime, lecture demonstrations could serve as media to help students integrate associated conceptual frameworks (e.g. Sokoloff and Thornton 1997, Buncick et al 2001, Chang 2011).

**Conclusion**

Although the tertiary students in the current study had learnt the four physical laws in their secondary school physics classes, most of them failed to integrate the associated models, particularly those involving more sophisticated laws. This indicates that the students had not acquired the related knowledge in a solid manner in their earlier school years. Under such conditions—asking students to undertake conceptual reasoning via watching a lecture demonstration without receiving any instruction in advance may be an excessively challenging instructional approach. Miller et al (2013) asserted that students tend to observe phenomena based on the underlying physics conceptions they are acquainted with, as was disclosed in the present study. They may not always see what the instructor demonstrates, particularly when the involved scientific principles are profound, consistent with the argument mentioned by Roth et al (1997). Therefore, it is pivotal that sophisticated and sufficient instructional guidance always be provided, regardless of students’ prior learning experiences.

It was also found that recent learning of the lecture content seemed to have affected the students’ selection of models/laws to explain the observed phenomena. That is, they tended to apply what they had just learnt to interpret the context encountered. This reflects that provision of relevant lectures may be more essential than group discussion in terms of eliciting valid models, especially when confronting unfamiliar and profound learning tasks.
Coherent with the assertion stated by Roth et al. (1997), this study also discloses that recent and sophisticated instructional mediation is important for students to evoke the scientific principles the instructor is attempting to deliver.

It is noted that this study is limited to using two specific types of instructional strategies (group discussion without prior lecture and individual reasoning with prior lecture) to investigate the students’ conceptual reasoning performance, due to limited time and resources. Nonetheless, the focus of the study is on examining the extent of the students’ conceptual understanding of electric circuits obtained from their secondary school years, as opposed to what they learned in their recent class lectures. The findings revealed in this study could hopefully provide future instructors and researchers with some insights regarding designing instructional materials to help students learn the studied subject more effectively.

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ORCID iDs

Ruey S Shieh © https://orcid.org/0000-0003-3076-2535

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