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Practical work or simulations? Voices of millennial digital natives

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Abstract:	Students nowadays grow up with electronic devices and are adept at navigating the virtual world. Practical activities may be more of a novelty for them than simulations. Using the topic of electric circuits as a context, we examined the ways in which Grade 11 students perceived and learned from practical work and simulations respectively. In this quasi-experiment study, a group of 19 students used a free online simulations package ‘Circuit Construction Kit’, while another group of 17 students learnt through practical work. We administered a validated instrument to both groups and found that practical work and simulations supported students' learning in similar ways. The interventions were then reversed so that all participants experienced both practical work and simulations. Finally, seven students from each group were selected for a group interview. Through the interviews, we identified features of simulations and practical work respectively that students believed contributed to their learning.

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Students nowadays grow up with electronic devices and are adept at navigating the virtual world. Practical activities may be more of a novelty for them than simulations. Using the topic of electric circuits as a context, we examined the ways in which Grade 11 students perceived and learned from practical work and simulations respectively. In this quasi-experiment study, a group of 19 students used a free online simulations package ‘Circuit Construction Kit’, while another group of 17 students learnt through practical work. We administered a validated instrument to both groups and found that practical work and simulations supported students' learning in similar ways. The interventions were then reversed so that all participants experienced both practical work and simulations. Finally, seven students from each group were selected for a group interview. Through the interviews, we identified features of simulations and practical work respectively that students believed contributed to their learning.

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Introduction

In the past two decades, e-learning tools such as simulations have been offered as novel learning experiences and as alternatives to practical work (Evangelou & Kotsis, 2019; Linn, 1998; Tao & Gunstone, 1999). However, few classroom studies have examined the affordances and limitations of practical work and simulations in particular to a fundamental shift in students' upbringing: students born after 2000 have grown up with various kinds of electronic learning devices. In this paper, we report our findings on how simulations and practical work enhanced students' conceptual understanding of electric circuits and on the features of these two learning environments that the students perceived to be conducive to their learning.

Literature Review

Learning through practical work

Practical work is an indispensable component of school science (Jenkins, 1980; NRC, 2012; Wang et al., 2014). School teachers have used practical work for over a hundred years because it is believed to motivate students and allow them to develop an understanding of abstract ideas from concrete situations (Evangelou & Kotsis, 2019; Gee & Clackson, 1992; Jenkins, 1980; Kapici, Akcay, & de Jong, 2019; Kirschner & Huisman, 1998; Myneni, Narayanan, Rebello, Rouinfar, & Pumtambekar, 2013). However, the development of theoretical understanding through practical work can be problematic. Hodson (1991) reported that practical work was sometimes 'ill-conceived, confused and unproductive', and further observed that '[for] many children, what goes on in the laboratory contributes little to their learning of science' (p. 176). It has also been noted that in practical work activities, students often see *what* is happening, but not *why* it is happening (Hodson, 1993; Kirschner & Huisman, 1998; Wellington, 1998). A previous study found little evidence that practical work, as practised by teachers, helped students to link observations with scientific concepts (Abrahams & Millar, 2008). Pedagogical noise in practical work and complicated procedures have also been found to result in poor learning (Hodson, 1991). In short, despite the time and effort invested in it by teachers and students (Blake & Scanlon, 2007; Hodson, 1993; Kirschner & Huisman, 1998; Triona & Klahr, 2003), practical work may result in confusing and counter-productive outcomes.

Overview of simulations

Because of technological advancements, today's students are more tech-savvy, and the use of digital technologies has become popular in classrooms. Although Jean Justice and

Ritzhaupt (2015) reported that some potential barriers were perceived by teachers in using simulations in teaching, simulations appear promising in fostering both hands-on and minds-on activities for students to learn abstract concepts (Barko & Sadler, 2013; Develaki, 2017; Kirschner & Huisman, 1998; Mayer, Warmelink, & Bekebrede, 2013). A simulation can be defined as a computer programme that represents a natural process or a theoretical model in which description, explanation, interpretation and/or prediction can be achieved (Koh, Kin, Wadhwa, & Lim, 2012; Ritzhaupt, Gunter, & Jones, 2010; Scaife, 1993). Simulations allow students different degrees of control during their investigations: some allow students to alter key variables to generate idealised results instantaneously, whereas others allow them to pursue their own investigations at their own pace. When the simulations are well utilized, they may reduce pedagogical noise. This not only provides teachers with additional opportunities to help students link observations to ideas but also encourages student-led scientific investigation. When learning flexibility and feasibility increase, the resulting autonomy may promote students' interest in learning.

Because simulations help students to experience scientific phenomena, link observations to scientific ideas and conduct investigations in a more flexible way, they not only enhance learning but also improve students' attitudes towards physics (Linn, 1998; Podolefsky, Perkins, & Adams, 2010; Tao & Gunstone, 1999; Zacharia & De Jong, 2014). Embedding simulations in lessons may be an effective means of promoting students' interest in and content knowledge of physics. Various studies have identified the advantages of simulations over practical work (Bumbacher, Salehi, Wieman, & Blikstein, 2018; McFarlane & Sakellariou, 2002; Unlu & Dokme, 2011; Zacharia, 2003). These studies are synthesised in Table 1.

[Please insert Table 1 here.]

The research studies cited above demonstrate numerous ways in which simulations support students' learning. However, in a critical review of research on the impact of computer simulations in K-12 and college science teaching and learning published between 1972 and early 2010, Smetana and Bell (2012) reported that certain studies support the effectiveness of practical work in conceptual understanding, while others support the effectiveness of simulations. More recently, Evangelou and Kotsis (2019) found no substantial difference in the conceptual understanding of frictional force between students who conducted practical work and those who learned through simulations. Overall, there is little evidence to show whether practical work or simulations is more effective in helping students link observations with scientific concepts. In fact, given that simulations have become more commony used, and that practical work will continute to be essential in the learning of science, instead of asking which of the practical work or simulations is more effective, it would be more fruitful to identity the ways that each of these learning experiences is conducive to learning (Puntambekar, Gnesdilow, Dornfeld Tissenbaum, Narayanan, & Rebello, 2021).

Challenges of learning about electric circuitry

Extensive research studies over the past 30 years have established that students develop a wide range of ideas and beliefs about electricity from their everyday experiences (Duit, Schecker, Höttecke, & Niedderer, 2014; von Rhöneck, Grob, Schnaitmann, & Völker, 1998). However, these ideas commonly differ from scientific understanding (Shipstone, 1984; Solomonidou & Kakana, 2000). Taking circuit phenomena as an example, Engelhardt and Beichner (2004) reported that some US high school and college students believed that current could be consumed and that a battery was a source of constant current. They also mistakenly interchanged scientific terms associated with circuits, such as *voltage resistance*, *energy* and *power*. Although various studies have identified difficulties that students face in learning about electric circuitry (Hart, 2008; Johsua, 1984; McDermott & Shaffer, 1992; Reiner, Slotta, Chi, & Resnick, 2000), researchers are still looking for effective pedagogical approaches to tackling these problems.

Studies have shown a number of advantages in using simulations for the teaching of electric circuitry (McFarlane & Sakellariou, 2002; Zacharia, 2003); however, there is little research comparing the effectiveness of practical work with that of simulations in enhancing high school students' learning about this topic. A summary of research examining on the use of simulations as an alternative to practical work is presented in Table 2.

[Please insert Table 2 here.]

While research on simulations indicates their promise, practical work also provides students with unique learning experiences. Osborne (2015, p. 21) argued that there is no substitute for practical work because it provides students with authentic first-hand experiences that stimulate their thinking and learning. In their critical review, Smetana and Bell (2012) concluded that the effectiveness of educational tools was limited by the ways in which they were used. Simulations were found to be most effective when they were used to supplement rather than replace other instructional modes such as practical work. As such, we are cautious about making definitive statements about whether simulations or practical work are more effective in facilitating students' learning. Specific factors such as how, with whom and on what topics they are used, and which concepts they aim to facilitate students' learning of should be considered. Focusing on a lesson about electric circuitry, this study compares students' learning through simulations with learning through practical work and examines students' perceptions of these learning experiences.

Linking observations to ideas

Many teachers might assume that practical work is a universal component of effective science learning. They anticipate that carrying out practical work, or increasing the amount of practical work, will lead to learning. In light of this, Abrahams and Millar (2008) proposed two levels of effectiveness for a practical activity: Level 1 refers to students' procedural understanding of the practical work, while Level 2 refers to students' achievement of the learning objectives set by teachers.

Research Questions

Given the debates surrounding the roles of practical work and simulations in enhancing high school students' conceptual learning of electric circuitry, this study addressed the following two research questions:

RQ 1: To what extent do simulations and practical work enhance students' conceptual understanding of electric circuits?

Smetana and Bell (2012) observed that 49 of 61 studies (either descriptive studies or comparisons with more traditional methods) reported the positive effects of the use of simulations. However, the studies they reviewed were published between 1972 and 2010. As mentioned above, today's students were born after the year 2000 and have grown up with various kinds of electronic devices, therefore past research may not be applicable to this current generation of students. However, little new research has examined the potential and limitations of practical work and simulations through classroom studies. We therefore thought it valuable to elicit students' views on the use of simulations and practical work as learning activities, and their opinions on which features of these learning environments they perceived to be conducive to their learning.

RQ 2: What features of simulations and practical work do students perceive as contributing to their learning?

We were interested in student talk in the context of simulations and practical work. We foresaw that students would comment on how practical work provided an authentic or real experience for them, and we therefore sought to identify why authenticity or realness was important to them (Puntambekar *et al.*, 2021). Besides, we also examined how the experience of practical work might contribute to learning in ways that are not achieved through the experience of clicking or typing in the simulations environment.

While student talk in the laboratory environment may revolve mainly around the procedural aspects of activities (Effectiveness level 1, after Abrahams & Millar, 2008), we envisaged that student interactions could also contribute to learning beyond clarifying procedures or equipment usage in ways that aligned with our analytical framework for assessing practical work. We thus aimed to identify how social interaction while handling laboratory equipment might contribute to students' learning.

We are aware that factors *perceived* by students as contributing to their learning may not be the factors that *actually* contribute to their learning. Nevertheless, we believe that students' views can help teachers and simulations designers develop strategies that best fit student interest (see for example, Oon, Cheng & Wong, 2020).

Method

Participants and expected learning outcomes

The participants of this study were 36 Grade 11 students (age 15-16) in a co-educational school in Hong Kong. They were randomly assigned to one of two groups: (a) the simulations group consisting of 19 students (15 male and 4 female students) or (b) the practical work group with 17 students (12 male and 5 female students). Prior to this study, the participants had already acquired fundamental knowledge of physics topics such as mechanics, heat and optics. For this unit, students were expected to learn concepts related to DC circuits, such as electric current, electrical energy and electromotive force, resistance, series and parallel circuits, simple circuits and electrical power. They were also expected to learn mathematical derivations related to DC circuits.

Treatment

In this study, we tried to ensure that the two groups were similar in composition, so we adopted a non-equivalent, quasi-experimental design (Campbell, 1963) and a mixed research method (Greene, Caracelli, & Graham, 1989).

In the simulations group, students spent 15 hours studying the topic direct current circuit (DC circuit) using the simulations software Circuit Construction Kit, whereas the practical work group spent 15 hours engaged in practical work on the same topic. At the beginning of the 15-hour intervention, each group participated in a half-hour revision session covering ideas related to DC circuits that they had learnt in Grade 8. The revision addressed concepts such as closed and open circuits, voltage, current, resistance and series and parallel circuits. The session also served as a venue for answering students' questions. The next section discusses the interventions more specifically.

Simulations group

The Circuit Construction Kit (CCK) software package used in the simulations group was available on-line for free [http://phet.colorado.edu]. The software was installed on 50 computers in the school computer room and on computers in the participants' homes. CCK simulated the behaviour of simple electric circuits and provided an open workspace where students could manipulate resistors, light bulbs, switches, wires, batteries, ammeters and voltmeters. The interactive simulations were highly visual. For example, they ‘showed’ the movement of electrons in the circuit. Students created circuits by clicking icons that represented electrical parts and by moving the parts to the desired position in the circuit. Students could also change the parameters, such as the resistance of the resistor and the voltage of the batteries.

After completing a circuit, the software would visualise the circuit’s behaviour, such as the brightness of the bulbs and the flow of the charges. By using simulated voltmeters and ammeters, the students were able to measure the current passing through any resistor and the voltage across any light bulb. The students then conducted a series of experiments in which they built circuits from the schematic drawings to determine the relationships of equivalent resistance in series and parallel circuits. By adjusting the resistance, they were able to measure the current passing through any resistor and the corresponding voltage across it to verify Ohm’s law. Table 3 summarises the teaching and learning activities of the simulations group.

Practical work group

Before the practical work group intervention began, the condition of all the equipment used, including wires, batteries, bulbs, ammeters, voltmeters and resisters, was carefully examined, and the number of each item was checked to make sure there was enough for all members of the group. This was done to minimise pedagogical noise. The students then carried out the assigned practical work activities. They first used wires to connect bulbs to form a closed circuit. They then used an ammeter and voltmeter to measure the current and voltage across the bulbs. They also varied the resistance of the resistors or voltage of the batteries, and observed the corresponding changes in the brightness of the bulbs or in the readings on the ammeters and voltmeters. As with the simulations group, students conducted a series of experiments to verify Ohm’s law: they built circuits based on schematic drawings to determine the relationships of equivalent resistance in series and parallel circuits, and they measured the current passing through any resistors together with the corresponding voltage across any resistors. Table 3 summarises the teaching and learning activities of the practical work group.

Exchanging learning interventions

After the 15-hour intervention, the simulations group were asked to undertake three hours of practical activities that the practical work group had engaged in, while the practical work group spent three hours on simulations using CCK. Thus, at the end of the intervention, all students had experienced both practical work activities and simulations. This was done to ensure that (1) the study did not cause students to be deprived of the learning experience of either practical work or simulations, and that (2) students would be able to compare their practical work and simulations experiences, thus facilitating data collection for the second research question.

Worksheets that included a sequence of experiments depicting every concept of DC electric circuitry were distributed. Table 3 shows the instruction and activity plans of the simulations and practical work groups.

[Please insert Table 3 here.]

Data collection

As mentioned above, the first research question was, ‘To what extent do simulations and practical work enhance students’ conceptual understanding of electric circuits?’ To answer this question, we adopted the Determining and Interpreting Resistive Electric circuit Concepts Test (DIRECT) (Engelhardt & Beichner, 2004) to evaluate students’ understanding of a DC circuit. DIRECT is composed of 29 multiple-choice questions with 3 to 5 options each. Questions in the instrument cover the learning objectives of the physics curriculum that the students were following in this study. These included topics related to four areas: (A) physical aspects of DC circuits, (B) energy, (C) current and (D) potential difference and voltage. The instrument was administered as a pre-test after the students had finished the revision of their Grade 8 materials. The same instrument was administered again as a post-test at the end of the 15-hour intervention.

We also measured the changes in students' attitudes after the intervention using the attitude instrument Intrinsic Motivation Inventory (IMI) developed by Ryan and Deci (2003). However, we do not discuss our findings regarding the students' attitudes in this paper because it is beyond the scope of our research questions.

To answer the second research question, group interviews were carried out on the features of simulations and practical work that students perceived as contributing to their learning. The students who were invited to participate in the interview were those whose DIRECT post-test scores were more than 20% higher than their pre-test scores, and those whose IMI scores also indicated a significant change in attitude (Table 4). Based on the selection criteria, 7 students (5 male and 2 female) from the simulation group and 7 students (3 male and 4 female) from the practical work group participated. During the interviews, students were first shown pictures that had been taken of both interventions to facilitate their recall, after which they were asked questions based on the pictures.

[Please insert Table 4 here.]

Data Analysis

To address the first research question, the data from DIRECT were evaluated using the SPSS 22.0 package programme. An independent sample t-test was first used to determine whether there were any significant differences between the pre-tests of the two groups. Then, since the data’s skewness and kurtosis indicated normal distribution, a paired t-test was used to determine whether there were significant differences between the pre-test and the post-test in each group. To facilitate the analysis, the DIRECT questions were categorised into four areas based on their correspondence to four different learning objectives falling under the overarching topic of electric circuits. Table 5 shows the summary of the four cognitive learning objectives and the corresponding relevant concepts. The pre-test and post-test results were compared according to these different cognitive learning objectives.

The mean, standard deviation and paired t-test results of both the simulation group and the practical work group are reported in the results section of this paper.

[Please insert Table 5 here.]

To address the second research question, selected students were asked about their learning experiences and the features of both the simulations and the practical work interventions that they perceived as contributing to their conceptual learning of the topic. The two interviews were transcribed and coded for content analysis.

In the analysis, we anticipated that students would comment on how practical work provided an authentic or real experience for them. We therefore aimed to identify why authenticity or realness was important for them as we wanted to examine the ways in which the experience of practical work might contribute to learning beyond clicking commands or typing numbers in the simulations environment. This was in line with recent literature arguing that learning abstract concepts is inseparable from the body's action and activities. We also examined the role of student talk. As mentioned above, we understood that student talk in the laboratory environment mainly revolved around procedural aspects of activities (Effectiveness Level 1, after Abrahams & Millar, 2008), but we also envisaged the possibility that talk might have contributed to student learning in ways that went beyond clarifying procedures or equipment usage. We thus aimed to identify how students's social interaction while handling the laboratory equipment might have contributed to their learning.

Results and Discussion

This study investigated (1) the effectiveness of simulations and practical work in developing students' learning of electric circuits and (2) students' views of their learning experiences. We adopted the Determining and Interpreting Resistive Electric circuit Concepts Test (DIRECT) and t-tests to evaluate the homogeneity of the two groups and significant changes from the pre-test to the post-test. We also compared the learning achieved by the two groups in the four topic areas: (A) physical aspects of DC electric circuits, (B) energy, (C) current and (D) potential difference and voltage. This allowed us to identify which areas of concepts were better facilitated by either simulations or practical work. Afterwards, in order to identify features that students perceived as contributing to their learning, we interviewed 7 students each from the simulations group (5 male and 2 female) and the practical work group (3 male and 4 female).

Findings related to the homogeneity of the two groups

There was a significant difference (t=2.164, p<.05) in DIRECT pre-test scores between the students in the simulations and those in the practical work group (Table 6). This suggests a difference in the baseline knowledge of the two groups. This meant that we could only compare the knowledge of each group of students before and after their respective interventions. We were unable to compare the enhancement of learning achieved through simulations or practical work, and therefore could not conclude which of the two interventions better enhanced students' learning.

[Please insert Table 6 here.]

The results above show that there was a statistically significant difference between the two groups (t=–0.038, p<.05), signifying that the two groups were not homogeneous. However, the different baseline and the small sample size meant that comparing the effects of simulations with those of practical work was unwarranted. The following section shows the effectiveness of both interventions for learning among the students, who had grown up with mobile technology.

Findings related to the pre-test and post-test scores of both groups

Both the simulations and the practical work group exhibited statistically significant gains in DIRECT scores (t=–4.595, p<.05 and t=–4.948, p<.05 respectively) (Table 7). These findings echo those in aforementioned research studies suggesting that simulations have an important role in enhancing students' learning (Unlu & Dokme, 2011; Zacharia, 2003), and that practical work (e.g. Freedman, 1997) is still essential for student learning.

[Please insert Table 7 here.]

In the comparison of the pre-test and post-test results within each of the four areas of cognitive learning objectives, the following results pertaining to the mean, standard deviation and the paired t-test were found. Table 8 reports the results for the simulations group, and Table 9 reports the results for the practical work group.

[Please insert Table 8 here.]

[Please insert Table 9 here.]

The simulations group showed a statistically significant gain in DIRECT area A (physical aspects of DC circuits) only (t=–6.938, p<.05). However, for the practical work group, statistically significant increases were found in three areas: physical aspects of the

DC circuit ($t=-4.181$, $p<.05$), current ($t=-3.082$, $p<.05$) and potential difference and voltage ($t=-3.312$, $p<.05$). That is, the practical work group showed a better conceptual understanding in two areas: current (e.g., conservation of current) and potential difference and voltage (e.g., their definitions). For example, in DIRECT question 1, students in the practical work group showed more improvement in recognizing the concept of charge conservation in area C (current). They also performed better on DIRECT question 6 (categorised as area D [potential difference and voltage]), which required them to rank the potential differences in different spots of a simple closed circuit consisting of a battery and a light bulb.

In sum, the paired t-test indicated statistically significant gains in the DIRECT pre-test and post-test results in both interventions, which showed that both simulations and practical work improved the grade 11 students’ conceptual learning about electric circuits. When the results were categorised according to the four cognitive learning objectives, the change between pre-test and post-test indicated that the practical work group demonstrated more improvement than did the simulations group in two specific areas: area C (current) and area D (potential difference and voltage). Nevertheless, we noted that the initial scores of the practical work group in these two areas were rather low. We were thus unable to rule out the possibility that their scores would also have improved significantly if they had been assigned to the simulations group.

Findings related to the Interviews

Feature of practical work: Excitement

School students nowadays grow up with electronic devices such as tablets and smartphones, and they are adept at navigating the virtual world. Although schooling has become heavily reliant on e-learning tools such as on-line assessment, flipped learning, and virtual reality learning, the lack of novelty that these tools have for these students may cause them to find these learning environments uninteresting or too informal. Such a loss in interest may lead to poor learning. On the other hand, practical activities might be more novel to them than e-learning experiences such as simulations. This may explain why students engaged in practical work showed higher levels of improvement in area C (current) and area D (potential difference and voltage) in the DIRECT instrument.

Research has pointed out some typical misconceptions about electric circuits, such as the idea that current is consumed, or that the battery is a source of constant current, and the mis-definitions of terms such as voltage, resistance, energy and power (Duit & Rhoeneck, 1998; Duit et al., 2014; Engelhardt & Beichner, 2004). In the present study, students reported that observations made about real objects in the course of practical work generated excitement. Such excitement may contribute to the learning of these concepts.

One student, George, said that changes in the bulbs' brightness were only represented by changes in the intensity of the yellow colour in simulations, a visualisation that did not sufficiently capture his attention. However, he noted that when he varied the voltage of the real batteries, 'the instant brightness change of the real bulb really was exciting and impressed me very much.' George further explained that when the parameters changed in the simulations, the visual effect of the changing yellow intensity of the bulb onscreen was not attractive at all because the effect was similar to the graphics in a video game. In contrast, when undertaking the practical work, the experience of actually varying the voltage of the batteries made him feel in control of the whole system. This generated feelings of excitement, even when the bulb blew. George also said that the experience left a deep impression on him, and that he would remember the parameters' relationship (the higher the voltage, the brighter the bulb) for a longer time. This statement demonstrated that he had a better understanding of the meaning of voltage in relation to power/energy, in contrast to common misconceptions about electric circuitry (Engelhardt & Beichner, 2004). This might contribute to his future learning about the topic.

Two students, Kelly and Hattie, shared views similar to those of George when they recalled their practical work that had led to a conceptual change regarding charge conservation. Kelly had originally held one of the common misconceptions mentioned by Engelhardt and Beichner (2004) that a battery is a source of constant current/charge. She said, ‘In the beginning, I strongly believed the charge would be used up after it lit up the bulb…. However, I was a bit shocked when I saw that the reading of the ammeter remained the same all the time in the circuit I built. I was wrong…. The experience was amazing and exciting.’ She also said that although the simulations had demonstrated the concept of conservation of charge/current in a similar way (with unchanging results on the ammeter), she had been sceptical about the reading in the simulations because the ammeter was virtual (rather than real) and everything had been ‘pre-set’ and ‘predicted’ by the computer programme. She had thought the reading might be merely for display.

The discussion above shows that the excitement generated by practical work was conducive to students’ learning, as it helped students learn the concepts better and made the experience more memorable. The interview data was also consistent with the findings from the DIRECT data. Both demonstrated that practical work might contribute to students’ learning, especially in concepts relating to area C (current) such as the conservation of charges and area D (potential difference and voltage), such as the definition of the term *voltage*. Apart from George, Kelly and Hattie, other students interviewed also shared the view that the experience of manipulating real objects in practical work generated excitement and contributed to learning.

Feature of practical work: Social interaction among peers

Learning abstract concepts is inseparable from the body’s action and activities. Students reported that practical work provided a good learning environment for social interaction among peers, a feature that might contribute to learning and that was not present in the simulations environment.

One student, Nancy, recalled her experience of dealing with the discrepancies between the values she expected to observe (based on her prior knowledge) and the actual readings taken during the practical work concerning the branched circuit's current. After Nancy and her groupmates had built a branched circuit, they found that the sum of the branched currents was not the same as the main current. She said, ‘… to identify the problem, we all worked as a team, we checked the theories in textbooks, such as the ohmic materials of circuit components and the definition of Ohm’s law, discussed the equations used like equivalent resistance in series/parallel circuits, double confirmed all the calculations and re-checked all the circuit contacts such as checking for poor connections together… .’ After several attempts to troubleshoot the setup, Nancy’s group finally discovered that the discrepancy was a result of the battery power drop rate being faster than they had expected. Although they were the last group to complete the experiment, they were content and satisfied because they were able to resolve the problem through collaboration/group work. In this experience, Nancy and her groupmates discussed the findings, built the circuit and solved the problems together. She said, ‘practical work provided an environment for interaction and discussion…. Even though you worked with classmates in simulations, the computer programme was tailored for one person to manipulate only. You did not have … problems in circuit building as everything was all set?' The opportunities for social interaction among peers were limited with the simulations. During the practical work, however, observations, ideas and knowledge learnt were exchanged and discussed among Nancy's groupmates; the social interaction was fruitful and contributed to their learning.

Another students, Dora, also said that her group interacted a great deal in the practical work session. She recalled an experience with problem-solving encountered by her group: 'When the polarities of the meters went wrong, no readings were recorded … or even worse, when the voltage of power supply was set too high, the bulb blew.' She further recounted, 'During practical work, we exchanged our observations and thoughts actively about the ammeters and voltmeter reading problems. We adjusted, relocated and reconnected the objects like batteries and bulbs. After some time, we justified our predictions at the end.' Dora reported that when similar situations happened in the simulations, the solution was easy. The situation only required one groupmate to 'undo the programme and start everything over at once…. It did not require you to prepare well or pay attention when you used simulations, because there were no consequences if things went wrong.' In sum, Dora found that practical work provided both the elements of excitement and social interaction between peers, which contributed to the students' learning. While simulations did facilitate discussion when problems arose, the simulations could be reset too conveniently and were usually controlled by a single person. The short amount of time and the limited amount of interaction required to fix the problem did not create an environment that encouraged student talk when problems arose.

In sum, students perceived the excitement generated by the novelty of practical work and an environment that encouraged social interaction between peers to be two features of practical work that were conducive for learning concepts in physics, especially concepts relating to current, potential difference and voltage. In contrast, the students found the actions of clicking and re-setting setups in the simulations swift and (too) convenient. As mentioned earlier, Smetana and Bell (2012) outlined the positive effects of the use of simulations in their critical review; however, the simulations may not be as effective for students born after 2000 who have grown up with digital technology.

Feature of practical work: Linking observations to ideas

We used the two-level effectiveness of practical work framework (Abrahams & Millar, 2008) to analyse Nancy's learning experience concerning the discrepancies in the expected and actual readings when her group constructed a branched circuit.

In the beginning, Nancy’s group tried to construct a branched circuit according to the teacher’s instructions (Level 1:o). However, Nancy reported that there was a reading discrepancy between the expected value and the experimental reading, so the members of the group started to think of the possible source of the error (Level 1:i). Working together, they focused on their observations (e.g. circuit connections from instructions, readings from meters) and cross-checked these with their expectations based on their conceptual understanding (e.g. equivalent resistance of series and parallel circuits, Ohm’s law theories that had been previously learnt) (Level 2:i). Nancy’s group originally thought that the discrepancy was due to poor connections. With the aid of the ammeter, the group checked all the connections and confirmed that they were in good condition. They then hypothesised that the discrepancy was due to inconsistencies in the power consumption of the light bulbs. However, the voltmeter readings of the individual bulbs were the same, negating this hypothesis. Finally, they discovered that the rate of the drop in battery power was faster than they had expected. Through the troubleshooting process, the students analysed their observations (data), applied their knowledge to justify their hypothesis and finally solved the problem on their own (Level 1:i, Level 2:i).

From this learning experience, Nancy demonstrated her understanding of building a branched circuit and her ability to use an ammeter and voltmeter as instructed. This was evidence of doing what the teacher had intended her to do from the design features of the task sheet (Level 1:o). Then, Nancy and her groupmates interacted and discussed the circuitry problem, applying the idea of electric current. This demonstrated that they were thinking about their actions and observations using the ideas that the teacher intended them to use (Level 1:i). Nancy also demonstrated an understanding that electric current is a flow of charges, and she applied Ohm's law when troubleshooting the problem. This was concrete evidence that she understood the concepts that the task was designed to help them learn (Level 2:i).

As mentioned earlier, the results from the DIRECT instrument indicated that the practical work group showed greater improvement than the simulations group in two specific areas: area C (current) and area D (potential difference and voltage). The interview data suggest that these findings may be explained by two features of practical work: excitement and social interaction between peers. These two features may cause practical work to lead to the formation of better linkages between observations and ideas.

In sum, the interview data revealed that the students were more intrigued and excited by results generated by 'real' physical equipment rather than by onscreen colour changes and numbers. Connecting and examining physical circuits together created a space where students could discuss and solve problems as a group. Moreover, the space also promoted better linkage between observations and ideas, which contributed to their learning.

Features of simulations: Solving the bridge-like circuit and switch circuit

Students reported that the simulations were convenient to use and represented concepts clearly and vividly. They also reported that the simulations provided flexibility in learning and gave better explanations of circuit behaviour than they experienced in the practical work, which contributed to their learning. Two students, Edward and George, said that the simulations were very useful for analysing some of the more uncommon types of circuits, such as a circuit with a branched switch (Figure 1) and a bridge-like circuit (Figure 2). George reported that the fast and instant responses of simulations not only saved a lot of time but also facilitated conceptual learning such as the definition of an open circuit and its related concepts like conservation of charge.

[Please insert Figure 1 here.]

The simulations group students performed better in the DIRECT questions concerning circuits with branched switches. For example, the students' score on DIRECT question 14 in the simulations group increased from 26.3% (pre-test) to 94.7% (post-test), whereas that of the practical work group only increased from 11.8% (pre-test) to 64.7% (post-test). For question 23, the pre-test and post-test results in the simulations group increased from 29.4% to 70.6%, whereas that of the practical work group only increased from 57.9% to 73.7%.

[Please insert Figure 2 here.]

Students also showed greater improvement in a DIRECT question about bridge-like circuits. For question 29, the score of the simulations group increased from 0% (pre-test) to 31.6% (post-test), whereas that of the practical work group remained the same at 11.8% in both the pre-test and the post-test.

Feature of simulations: Self-directed learning

With the advancement of technology, simulations nowadays are easy to operate and can be accessed anywhere. These features of simulations were cited in the group interviews. One student, Frank, said, ‘I used simulations at home also, which promoted self-directed learning. Sometimes, I built strange circuits to affirm my hypothesis and verify my understanding when I met difficult questions.’ Apart from the ease of setting complicated circuits and instant results, students found that simulations provided learning flexibility because they could be used anywhere and at any time.

As mentioned above, the interview data revealed some of the advantages of practical work over simulations, such as the encouragement of social interaction, which was less likely to occur in simulations, where clicking and re-setting the on-screen setups were swift and (too) convenient. However, simulations allowed students to explore complicated setups with instant results in their own time and space.

Conclusion

This study investigated how practical work and simulations facilitated student learning when students were being taught about electric circuitry, as well as students' perceptions of these learning experiences. We argue that these students, as members of a millennial digital generation, who have grown up with mobile technology, have opinions about practical work and simulations that may differ from those of students who were the subjects of research work undertaken when simulations was a still a novelty. The results showed that while both learning environments supported student learning, students who engaged in practical work showed a greater improvement in learning in two areas: current and potential difference/voltage. Interview data revealed that the students were more intrigued and excited by the results generated using 'real' physical equipment than they were by onscreen colour changes and numbers. In this way, our findings are consistent with the findings from classroom data that practical work and simulations supported different aspects of learning of science (Puntambekar, et al, 2021). In light of the analytical framework used to assess the effectiveness of practical work (Abrahams & Millar, 2008), features of practical work such as excitement and peer social interaction featured in the interviews as possible explanations for the development of better linkages between observations and ideas. This echoed the findings from the DIRECT instrument and Osborne (2015, p. 21), who stated that there is no substitute for practical work as it provides students with an authentic first-hand experience that makes the ideas they learn more plausible. Practical work is more than just a ‘less boring alternative’ to science learning.

Although connecting and examining physical circuits together created a space where students could discuss and solve problems, such a space for social interaction was less likely to occur in simulations, where clicking and re-setting setups were swift and (too) convenient. On the other hand, simulations allowed students to explore complicated setups with instant results in their own time and in any location. These findings point to the need to determine which learning environments are the best fit for the needs and preferences of millennial digital natives.

Limitations of the study and suggestions for future research

In this study, there was a two week gap between the end of the interventions and the group interviews, which may have affected the ways in which students perceived their learning experiences. Although we used photos of the lessons to help students recall their experiences, it would have been better if there had been a shorter time gap between interventions and interviews. Given that the sample was composed of only 36 participants, and that there were only 15 hours of intervention in a single school, our findings cannot be generalised to other contexts. Therefore, future studies involving both interventions and more students are recommended because students may come from more diverse backgrounds.

Since the generation Z students in this study had grown up with various kinds of electronic devices, they reported that practical work provided excitement and social interaction with peers, which contributed to their learning. As such, future studies involving longer intervention times (i.e., more than 15 hours) or other topics (e.g., force and motion in mechanics) may provide more opportunities for students to explore and reflect on their learning.

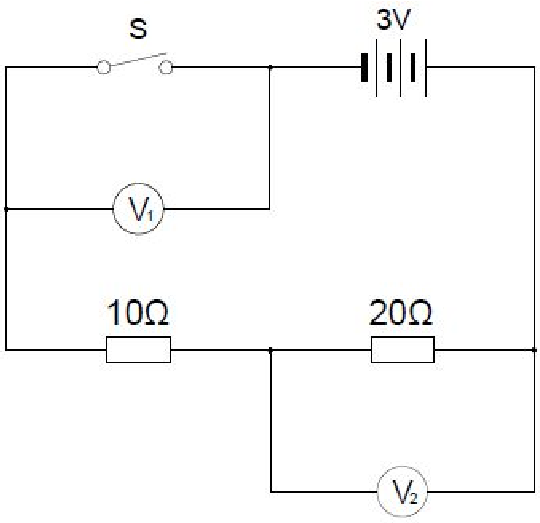

Figure 1 Example of a question on a circuit with switch.

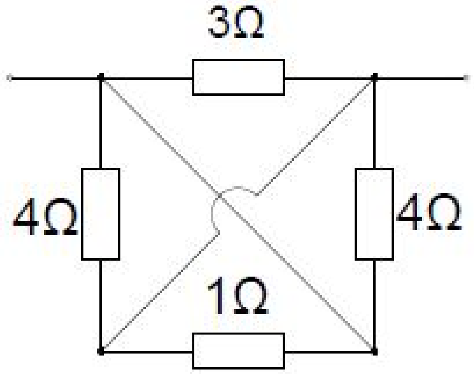

Figure 2 Example of a question on the bridge-like circuit.

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Table 1 Advantages of simulations over practical work

	Practical work	Simulations
Physical Setting	Poor apparatus conditions and limited resources which lead to teacher-led (pre-designed) demonstrations.	The condition of the equipment is always good and the number is unlimited.
Use of time	Too much time is spent on trivial procedures. Open investigation takes a long time before satisfactory completion.	Easily accessible; saves students and teachers time in preparing and setting up the ‘experiment’.
Teachers’ feedback	The supervision and assessment of laboratory work is often inadequate. Teaching value is low and constructive feedback is often lacking.	The instant results allow teachers have more time to give feedbacks to students for facilitation. Thus, they better help students to link

		observations to ideas (content knowledge).
Students’ interest	Students feel bored as activities done in practical work simply verify something already known.	Students can design their own ‘experiment’ (different degree of inquiry), which provokes their learning interest and excitement.
Students’ autonomy	Limited to school hours and school facilities.	They can be accessed beyond school hours and school facilities, which promotes self-directed learning.

Table 2 Summary of research on using simulations over practical work.

Author (Year)	Country of Origin	Participants	Research Interests
Ronen and Eliahu (2000)	Israel	High School	Achievement Process Skills
Zacharia (2003)	Cyprus	University	Attitude
Engelhardt and Beichner (2004)	USA	High School /University	Achievement
Finkelstein et al. (2005)	USA	University	Achievement Process Skills
Baser (2006)	Turkey	University	Achievement Process Skills Attitude
Zacharia (2007)	Cyprus	University	Achievement
Jaakkola and Nurmi (2008)	Turkey	Elementary	Achievement
Tarekegn (2009)	Ethiopia	High School	Achievement Process Skills
Farrokhnia and Esmailpour (2010)	Iran	University	Achievement Process Skills

Unlu and Dokme (2011)	Turkey	Elementary	Achievement
Jaakkola, Nurmi, and Veermans (2011)	Turkey	Elementary	Achievement Process Skills

Table 3 Instruction and activity plans for both simulation and practical work groups.

Topics	Learning activities / goals	Simulation Group	Practical work Group
Electric current, electrical energy and electromotive force	By using simulations software (for the simulations group) or real objects (for the practical work group), students built circuits to study the properties of current, voltage, electrical energy and EMF in a simple circuit. We expected that students would recognize that current flows through any resistor remained the same and the voltage sum across different resistors was the same as the EMF.	Simulations Activity 1	Practical Work Activity 1
Resistance	By using simulations software (for the simulations group) or real objects (for the practical work group), students built circuits to adjust the resistance to vary the current flowing through the circuit. Given	Simulations Activity 2	Practical Work Activity 1

	the reading of the voltage across the resistors, students may find out the relationship between the current and the voltage of a resistor (Ohm's Law).		
Series & parallel circuits and combined circuits	By using simulations software (for the simulations group) or real objects (for the practical work group), students built circuits from schematic drawings to find out the relationship of equivalent resistance of series circuits and parallel circuits.	Simulations Activity 3	Practical Work Activity 2

Table 4 A summary of the students' scores in DIRECT

Group	Student Name	Gender	DIRECT		
			Pre-test mean	Post-test mean	Percentage change
Experimental	Albert	Male	13	21	61.5
	Ben	Male	14	17	21.4
	Carol	Female	14	21	50.0
	Dora	Female	10	16	60.0
	Edward	Male	11	22	100
	Frank	Male	12	17	42.7
	George	Male	16	25	56.2
Control	Hattie	Female	18	23	27.8
	Ivan	Male	15	21	40.0
	Jenny	Female	11	14	27.3
	Kelly	Female	6	21	250
	Larry	Male	11	15	36.4
	Mark	Male	12	20	66.7
	Nancy	Female	15	19	26.6

Table 5 Summary of different cognitive learning objectives with relevant concepts in DIRECT

Cognitive Learning Objectives	Relevant concepts in electric circuit	DIRECT Question Number
(A) Physical aspects of DC electric circuits	(i) identifying and explaining a short circuit (ii) understanding the functional two-endedness of circuit elements (elements have two possible points with which to make a connection) (iii) Identifying a complete circuit and understanding the necessity of a complete circuit for current to flow in the steady state (iv) Applying the concept of resistance in series and parallel circuits (v) Distinguishing among different types of circuits such as series, parallel and combinations of the two.	4, 5, 9, 10, 13, 14, 18, 19, 22, 23, 27
(B) Energy	(i) Applying the concept of power to a variety of circuits (ii) Applying a conceptual understanding of	2, 3, 12, 21

	conservation of energy and the battery as a source of energy	
(C) Current	(i) Understanding and applying conservation of current to a variety of circuits	1, 8, 11, 17, 20
	(ii) Explaining the microscopic aspects of current flow in a circuit	
(D) Potential difference and voltage	(i) Applying the knowledge that the amount of current is influenced by the potential difference	6, 7, 5, 16, 24, 25, 26, 28, 29
	(ii) Applying the concept of potential difference to a variety of circuits	

Table 6 The mean, standard deviation and independent sample t-test results related to the DIRECT pre-test scores of the students in the simulation and practical work group.

Group	N	Mean	Std. deviation	t	p
Simulation group	19	14.37	3.59	2.164	0.038
Practical work group	17	12.06	2.68		

Table 7 The DIRECT paired t-test scores of both groups of students.

Group	N	Pre-test	Post-test	t	p
Simulation group	19	14.37	18.79	–4.595	0.000
Practical work group	17	12.06	17.18	–4.948	0.000

Table 8 The mean, standard deviation and paired t-test results related to the pre- and post-test scores of the students of the *simulation group*.

Cognitive Learning Objectives		Pre-test		Post-test		Paired t-test	
		mean	SD	mean	SD	t	p
A	Physical aspects of DC electric circuits	5.21	1.47	8.53	1.71	-6.938	.000
B.	Energy	2.47	1.31	2.84	0.90	-1.326	.202
C.	Current	1.95	1.13	2.42	1.07	-1.924	.070
D.	Potential difference and voltage	4.74	1.05	5.00	2.03	-.492	.628

Table 9 The mean, standard deviation and paired t-test results related to the pre- and post-test scores of the students of the *practical work group*.

Cognitive Learning Objectives		Pre-test		Post-test		Paired t-test	
		mean	SD	mean	SD	t	p
A	Physical aspects of DC electric circuits	4.88	1.27	7.00	1.70	-4.181	.001
B.	Energy	2.18	0.81	2.76	1.15	-1.975	.066
C.	Current	1.29	0.99	2.41	1.18	-3.082	.007
D.	Potential difference and voltage	3.71	1.05	5.00	1.46	-3.312	.004

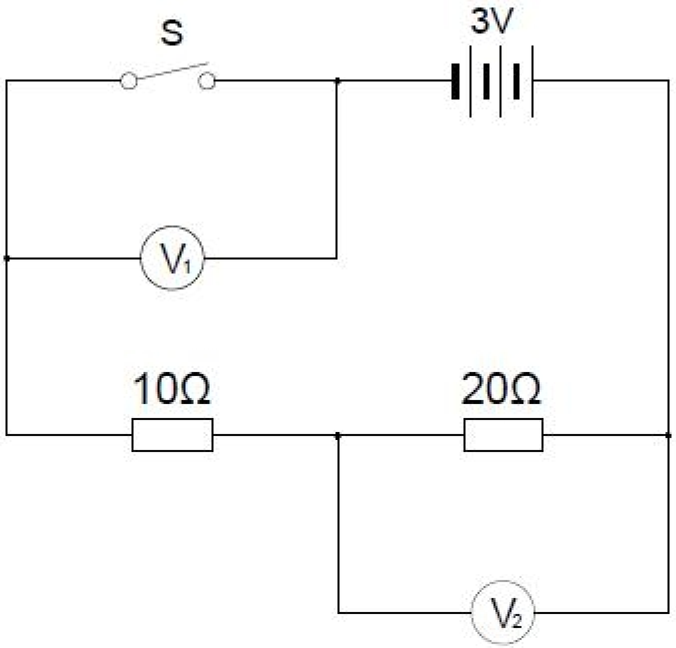

Figure 1 Question example of a circuit with switch.

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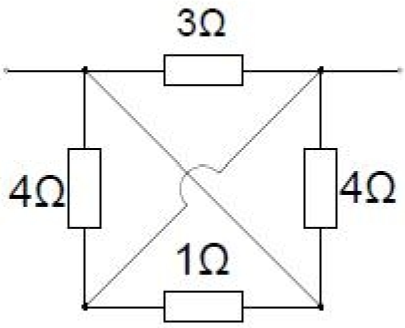

Figure 2 Question example of the bridge-like circuit.

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