# Smartphones, simulations, and science learning: rethinking physics experiments

Frank Angelo A. Pacala[1], Melody Rose M. Pacala[2]

[1]Presidential School in Karshi, 1 Mustaqillik Str., Karshi city, Kashkadarya province, 180100, Uzbekistan
[2]Karshi City School No. 1, 25 I. Karimov Str., Karshi city, Kashkadarya province, 180100, Uzbekistan

## Abstract

The explosion of different learning tools for science experiments has been evident in this century. Tools like smartphones and online simulations have catapulted science experiments to greater heights. Most studies on these emerging technologies are quantitative in method, so the literature noted that there is a need for qualitative studies in this field to fully understand the effect of these tools on students. This case study was undertaken to explore the lived experiences, perceptions, and feelings of the students exposed to smartphone-based experiments and online simulations. The study followed a comprehensive framework for case study, including preparation, collection, analyses, and sharing. There were eight participants whose ages were 15-17 years, and their parents and they signed the informed consent form. The data collection methods used were semi-structured individual interviews, monitoring, and observations. A thorough structural analysis was performed, and hermeneutic interpretation was followed to analyze the transcripts. These approaches and methods were successful in revealing three main themes: the affordances of smartphone-based experiments and online simulations, the enhancement and complementing of the role of digital tools in traditional hands-on experimentation, and the challenges associated with smartphone and online simulations in experiments. The affordances included increased student engagement, practicality and accessibility of learning, connection to reality, and enhanced conceptual understanding. The complementary role of smartphones and online simulations to traditional experiment setups is unique in this paper. However, the challenges are related to cognitive and technical limitations, equity issues, and the accuracy of the data gathered. Based on these conclusions, the study recommends training in the mentioned digital tools for teachers and students and smartphone policy for schools to avoid lesson disruption and addiction.

## Keywords

case study, conceptual understanding, engagement, hermeneutic interpretation, PhyPhox, PhET interactive simulations, smartphones-based experiments



## 1. Introduction

If you can recall an experience from your years studying science, you may think of using laboratory equipment and the enjoyment of learning through it. However, this experience is not singular, as many schools worldwide have limited opportunities to purchase and use science equipment in classes. Using conventional science equipment has remained a fundamental part of schools, but limits the ability of students to explore and be flexible independently.

To foster independent exploration and enhance flexibility in conducting science experiments, recent developments in smartphone-based sensors and online simulations like PhET have redefined how science should be taught and experienced by students. These tools have enabled students to become independent learners and have simplified data collection for analysis [1]. The tools mentioned have significantly transformed learning by bringing abstract concepts closer to reality [2]. The summary of studies in the conference papers of Papadakis et al. [3] suggested that computer simulations and cloud-based technologies can help in personalised learning and higher academic achievement of students.

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frankpacala@gmail.com (F. A. A. Pacala); maguadmelodyrosetuan0@gmail.com (M. R. M. Pacala)
https://scholar.google.com/citations?user=bvFlCogAAAAJ (F. A. A. Pacala); https://www.facebook.com/meldmaguad (M. R. M. Pacala)
0000-0001-5774-0008 (F. A. A. Pacala); 0000-0004-9250-2016 (M. R. M. Pacala)

While there are high hopes for smartphone-based experiments and online simulations in science [4], limitations exist in using smartphone sensors and online simulations for data collection. Not all sensors are compatible with every phone, meaning one cannot conduct the experiment if it is not built into the device [5]. According to Xia et al. [6], the results can yield false positives or false negatives due to limited range and sensitivity. Online simulations often lack physical interaction and have a narrow scope of exploration, and students may feel confused if they have little computer exposure [7].

To balance it out, schools must reconsider how science classrooms are structured. While smartphone-based experiments and online simulations have disadvantages, these are outweighed, especially for schools with low annual budgets. Students do not require highly sophisticated and sensitive sensors, as they typically use smartphones and simulations to validate scientific theories, such as measuring acceleration due to gravity or the value of static friction. Common smartphone applications for data collection and analysis include Phyphox, Physics AI, and Physics Toolbox Sensor Suite, whereas the most popular online simulation is PhET interactive simulations by the University of Colorado Boulder. According to Klein et al. [8], preparing low-cost experiments with smartphones has verified scientific principles and made experiments more engaging and enjoyable for students. The students in this research were exposed to Phyphox and PhET simulations for nearly one school year.

The theoretical underpinning of this paper is from the Technology Acceptance Model (TAM), which explores how students perceive the integration of online simulations and smartphone-based experiments in learning physics. This model comprises constructs that explain behavioral intentions in using technology. These constructs are perceived usefulness, ease of use, and attitudes towards technology [9]. These three constructs are aligned with this paper's objectives.

To explore the use of these emerging technologies, this study gathered the perspectives of students who were exposed to smartphone-based experiments and online simulations throughout the school year. By collecting these narratives from the students, the paper reveals their actual lived experiences, perceptions, and feelings regarding the use of these technologies. Most studies on smartphone-based learning (e.g., Hochberg et al. [10]) and online simulations (e.g., Yunzal Jr and Casinillo [11]) are quantitative in nature, while very few are qualitative. Tsai et al. [12] suggested that more qualitative studies in this field are needed to understand better the relationship of various constructs like engagement and conceptual understanding. Also, the data can inform developers on how to adjust their technologies based on students' experiences and insights. This information can also help educators and school leaders design a science curriculum that includes smartphones and online simulations among the available resources.

Based on the significance of the endeavor, this study aims to explore how the students lived experiences, perceptions, and feelings of the students exposed to smartphone-based experiments and online simulations. This study will answer the following questions:

1. How do smartphones and PhET help conduct physics experiments more effectively?
2. How do smartphone-based experiments features improve the learning experience?
3. How comparable is the experience using smartphones and PhET simulations to conducting traditional hands-on experiments?
4. What challenges are evident when using smartphones for physics experiments?

## 2. Methodology

### 2.1. Research design

This research is a case study of eight students in School A in Uzbekistan. A case study approach is appropriate in this study due to the limited number of participants who agreed to the informed consent form. Gerring [13] argued that a case study is a holistic understanding of a constituent unit to represent the larger class. According to Baškarada [14], the ideal number of participants in a case study is from 8 to 12. The sampling procedure followed is voluntary participation. Only those who signed the informed-consent form were involved. Therefore, selection bias is eliminated using this process. The study followed the case study framework of Baškarada [14], which followed preparation, collection, analysis, and sharing.

For transferability, thick descriptions of the educational context, instructional design, and participant profiles allowed readers and practitioners in similar educational environments to judge the findings' applicability to their contexts.

This study received ethical approval from the Presidential School of Qarshi. Informed consent was obtained from all participants and their guardians. Participation was voluntary, with the right to withdraw at any time. Confidentiality was maintained through anonymized data and secure storage.

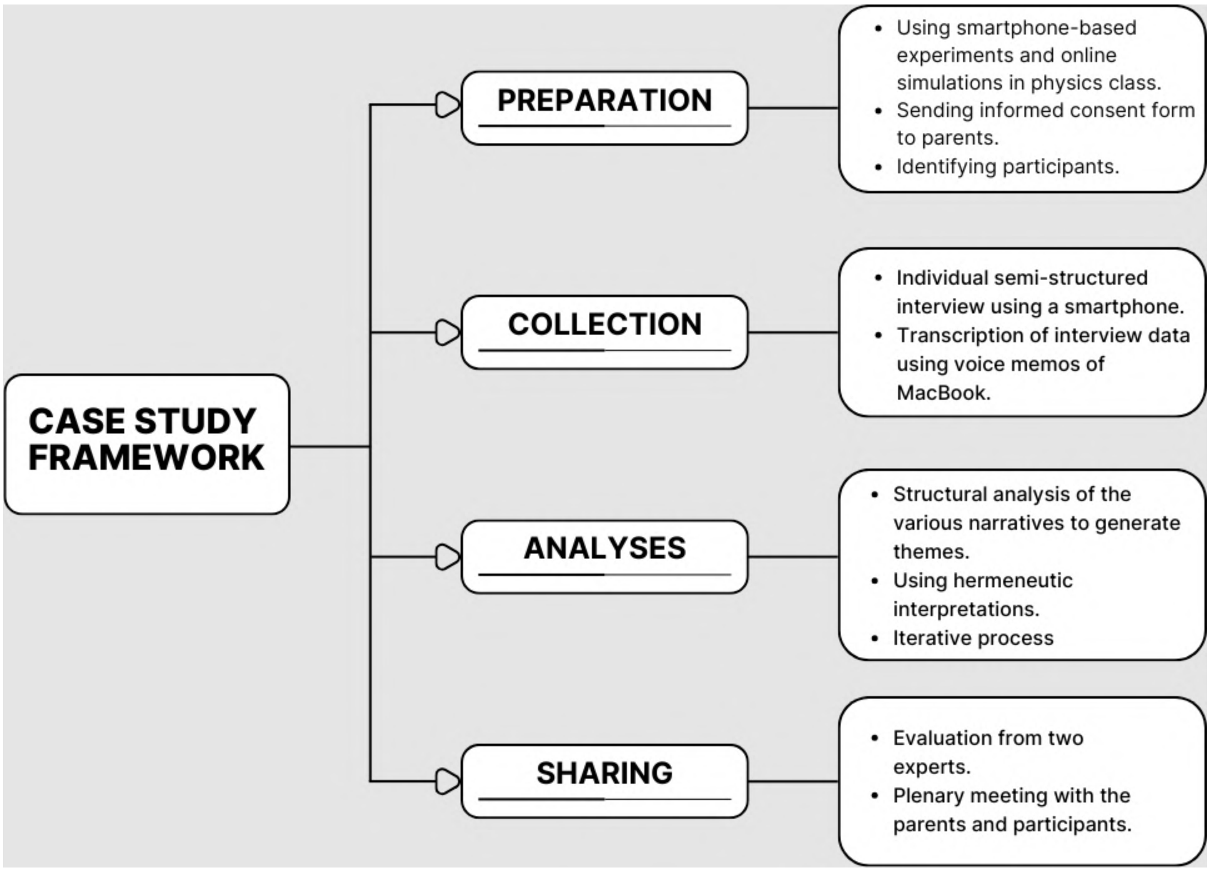


**Figure 1:** The study followed successive steps for a case study, such as preparation, collection, analyses, and sharing based on Baškarada [14].

## 2.2. Research participants

This study involved eight students. Two are ninth-graders, three are 10th-graders, and three are 11th-graders. The selection criteria are one school year of exposure to smartphone-based experiments and online simulations in physics, conducting at least one experiment utilizing those emerging technologies mentioned, age ranges from 15 to 17 years, and approval from their parents using the informed consent form. The students were exposed to the said emerging technologies for one school year and they were involved in at least five experiments made using such tools. The names of the participants were not mentioned in any section of this document to maintain confidentiality and anonymity; instead, they were given pseudonyms such as students A through H.

## 2.3. Data collection tools and procedure

The study used the following tools: a semi-structured interview guide, a smartphone for recording the interviews, and voice memos from a MacBook computer for data transcription. The semi-structured

**Table 1**
The structural analysis of narratives from Student A.

| Statement | Meaning units | Condensation | Subthemes | Themes |
|---|---|---|---|---|
| Smartphones and PhET make experiments much easier and faster to set up. With PhET, I can visualize concepts that are hard to demonstrate in class, like waves or electricity. The interactive simulations allow me to change variables and instantly see results. With smartphones, I can measure real-time data using sensors, which saves time compared to manual measurements. It feels more efficient, and I can focus on understanding rather than just the setup. – Student A | Smartphones and PhET make experiments much easier and faster to set up. | having faster and simpler experiment setup | Efficient setup | Practicality in science learning |
| | With PhET, I can visualize concepts that are hard to demonstrate in class, like waves or electricity. | Visualizing difficult concepts | Visualizing the invisible | Enhancing conceptual understanding |
| | It feels more efficient, and I can focus on understanding rather than just the setup. | focusing on learning rather than setup | Focused learning | Increasing learning efficiency |

interview guide contains six questions, primarily those aligned with the research questions at the end of this paper's introduction. An iPhone 15 was used to record the interview with the consent of the parents and students. These audio data were transcribed using the free voice memo software embedded in the MacBook computer.

Before starting this research, a letter of approval was sought from the school principal. Then, during the teacher-parent conference, the researcher introduced the details of the study to the parents. They were given the informed consent form to sign if they agreed their child would participate in the study. Those who did not sign were informed that there were no consequences, such as on the student's academic grades. In addition, those who signed up were told their child could withdraw from the study anytime.

Only eight students participated after those meetings. The interviews lasted from 40 minutes to one hour, and all data were gathered in five days. The language of the interview was English, and given the English level of the participants, interview data editing was performed but retained the participant's thoughts and ideas.

## 2.4. Data analyses

The transcribed data were analyzed using structural analysis. This process systematically cultivates themes by taking meaning units and condensing narratives [15]. The process started by plotting the interview data in MS Excel. Each participant's answer was analyzed, and the meaning units were taken. The narratives were read and re-read during this process to clearly understand their meaning. The meaning units were condensed by taking the essential meanings of each meaning unit using as many common words as possible. The condensed statements were sorted and abstracted to form subthemes. Finally, all subthemes were organized into main themes. A sample is shown in table 1.

When the data were organized into a table in MS Excel, they were further analyzed using hermeneutic interpretation. This means the students' narratives and themes were interpreted using their cultural, personal, and intellectual upbringing. In this way, the data were interpreted with their lived contexts for richer, more meaningful insights. The process was not only about categorizing the responses, but about seeking meaning behind each statement, considering the social realities of the learners and the educational exposure. While a single coder conducted the initial analysis, peer debriefing was employed to validate code consistency, and member checks were performed in both the final plenary and a follow-up verification session to confirm thematic resonance. This process improved both the credibility and the confirmability of the findings.

Patterns were identified based on frequency and the depth and complexity of the insights of the participants. The researchers continuously reflected on their biases, maintaining reflexivity throughout the analysis. This means returning to the students and asking them what they meant by that statement. The researchers also returned to the related literature to compare the experience of the participants with that of other students from another country or to verify them from the existing body of knowledge. In this way, the hermeneutic process allowed for a rich and contextual interpretation that respected the individuality of each student's voice while highlighting common themes relevant to the collective learning experience.

### 2.5. Sharing of the data

A plenary meeting was held with parents and students to inform them of the data results. The participants were asked if they agreed with the themes, and they found that the themes truly reflected their lived experiences, perceptions, and feelings. The researchers also sought questions from the audience and asked for minor clarifications relevant to their narratives and experiences.

## 3. Results and discussion

### 3.1. Main theme 1: Affordances of smartphone-based experiments and online simulations

The participants perceived and experienced several key affordances and benefits of smartphone-based experiments and online simulations in learning science. These include increased student engagement, connection to reality, enhanced conceptual understanding, and practicality and accessibility of learning. These themes were very common among the eight participants in this case study.

It should be noted that this was the first time that the participants were immersed in this kind of classroom strategy. Most students even stated that they had not conducted experiments in their previous grade levels in their science subjects. Experience a new way of learning is somehow exciting and fun [16]. All the participants experienced increased engagement and activeness in the lessons using these interventions. Student B claimed, "It's like playing and learning at the same time" and Student D added, "They make the learning process more interactive". Lim [17] supported this experience of the students. In his study, smartphone-based tools increased student-to-study and teacher-to-student engagement and interaction.

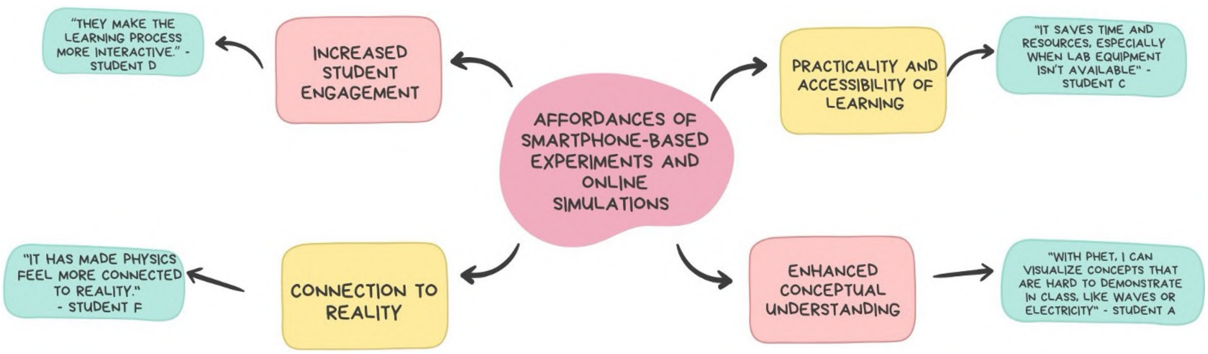


**Figure 2:** Four themes encapsulate the affordances of smartphone-based experiments and online simulations: increased student engagement, connection to reality, enhanced conceptual understanding, and practicality and accessibility of learning.

Most of the students reported that their previous teachers were somehow used to theory-based and lecture teaching methods. This is not a common theme, especially in developing countries like Uzbekistan. Marmah [18] claimed that the lecture method is the most traditional and common practice in most developing countries. The reason is that it is more economical and does not need laboratory equipment [19]. This becomes problematic when this method is extensively used throughout the school year. In this paper, students narrated how smartphone-based experiments and online simulations connect their study to reality. Student G said, “It made me feel that science is more accessible and part of everyday life, not just something you do for school”. This is supported by student F, who exclaimed, “It has made physics feel more connected to reality”. This is a similar perception from the students of Hochberg et al. [10]; however, their study is not qualitative. Unlike in traditional experiments, data may not be easy to generate, and accuracy is also under question. This problem not only hinders scientific conception but also disconnects the students from what reality is expected to be. Radu et al. [20] and Coramik and İnanç [21] said that smartphone-based experiments were able to bridge the abstractness of science and what reality is. For instance, the displacement-time graph of an oscillating body is now easily generated in applications like PhyPhox and is more easily understood by students regarding its scientific principles.

The next theme is about an enhanced conceptual understanding of physics. The students reasoned out that this is evident because of increased engagement and its connection to reality. The previous two themes are connected to this third theme and explanations to it. Student B said, “PhET simulations help me understand abstract concepts by showing visuals that I can interact with”. To support this, student G narrated, “It’s like doing both experiment and analysis at the same time, which helps me learn more deeply”. This occurrence is similarly observed by Milner-Bolotin and Milner [22], whose preliminary results concluded that smartphone-based experiments can boost conceptual understanding, while Rahmawati et al. [23] said that PhET simulations could increase comprehension in science and decrease the misconceptions held by students.

The lack of laboratory equipment is a common problem in developing countries. This was exacerbated during the COVID-19 pandemic when schools turned online. Ferri et al. [24] argued that this phenomenon has declined student participation and engagement in lessons and deepened the learning curve among students. With the advent of smartphone-based experiments and online simulations, experiments have now become more accessible and practical to both students and teachers. This is the fourth theme, which students overwhelming held that these merging technologies were accessible and practical to use. As narrated by Student C, “It saves time and resources, especially when lab equipment isn’t available”. Student E claimed, “I really like using the sensors. For instance, when studying motion or forces, I can use the Phyphox and instantly get data”. Pacala and Pili [25] argued that smartphone-based experiments can be done even at home with guidelines set by the teacher. So even during times of school interruptions like typhoons, earthquakes, etc., learning shall continue. However, schools should set policies on the use of smartphones in schools because the Organization for Economic Co-operation and Development (OECD) noted that 65 percent of member countries reported distraction from digital devices, including smartphones and computers, and affected their PISA scores [26].

These affordances are aligned with TAM. Many students appreciated the ease of using their own smartphones, noting that the tools were familiar and intuitive. These responses reflect perceived ease of use, suggesting that the students felt minimal effort was needed to operate the simulations and apps. Also, students’ narrations indicated that the smartphone-based experiments enhanced their conceptual understanding of abstract topics, such as light and force. This aligned with the TAM’s perceived usefulness construct, where students recognized the activities as beneficial for their academic performance and science comprehension.

### 3.2. Main theme 2: Enhancing and complementing the role of digital tools to traditional hands-on experimentation

Main theme number 2 summarized the perceived comparison of smartphone-based experiments and online simulations. The student’s general impression was that these emerging tools enhanced and complimented the traditional way of doing experiments. The themes under this main theme are the complementary role of traditional and digital tools and the flexibility and speed of digital tools.

Furió et al.'s study [27] observed the enhancement and complementary ability of augmented reality (AR), which suggests that other emerging technologies, such as smartphones and online simulations, can do the same. This research may be the first one to notice this phenomenon for smartphones, as students narrated. Student A said, "Traditional experiments are good because you physically handle materials and equipment, but they can be time-consuming and sometimes messy". Student D claimed, "Comparing online simulations and traditional to measure the value of acceleration due to gravity has been supplementing my knowledge". Other authors have compared online simulations with physical and traditional experiments, such as those by Brinson [28].

The Phyphox application can measure the acceleration due to gravity. Traditional apparatus, such as iron stands, clamps, balloons, or any falling object, can be used. The smartphone can act as a data collector for the time of the object's fall. Another idea is using a smartphone to collect data on the magnetic flux density of a solenoid, as shown in figure 3. In these ways, the smartphone complements the traditional experiment.

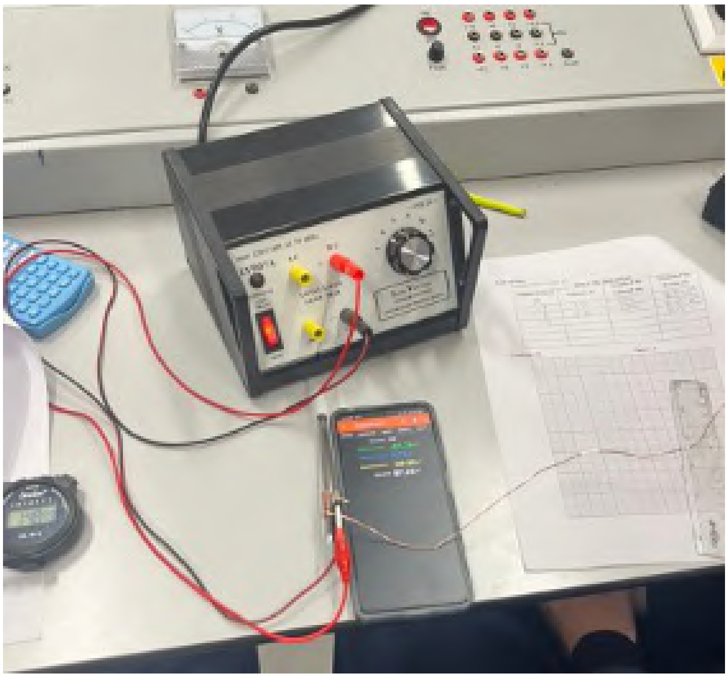

**Figure 3:** Smartphones complement traditional experiments by collecting magnetic flux density data of a solenoid.

This experiment method has been perceived as a flexible and fast way for the students to collect data. Student A exclaimed, "With smartphones and simulations, I feel like I can explore concepts more quickly and repeat experiments easily". Student E supported this idea; she said, "We were able to calculate the value of acceleration due to gravity quickly". This theme supported the previous theme on practicality and accessibility. For instance, measuring the magnetic flux density can be a difficult task without the Tesla meter, an instrument that can be expensive to purchase by low-budget schools. With smartphones, this can now be an easy task. This experience of the students is similar to the experience revealed by the students of Chu et al. [29]. They further observed that their students perceived the smartphone-based experiments as positive and enhanced engagement and understanding of the lesson.

### 3.3. Main theme 3: Challenges of smartphone and online simulations in experiments

Despite the promising results of using smartphones and online simulations in physics lessons, these technologies have limitations that pose challenges to both students and teachers. In this paper, the students narrated four themes that encapsulate the challenges of smartphone and online simulations in experiments: cognitive challenges, technical limitations, equity issues, and challenges in accurate data collection (figure 4).

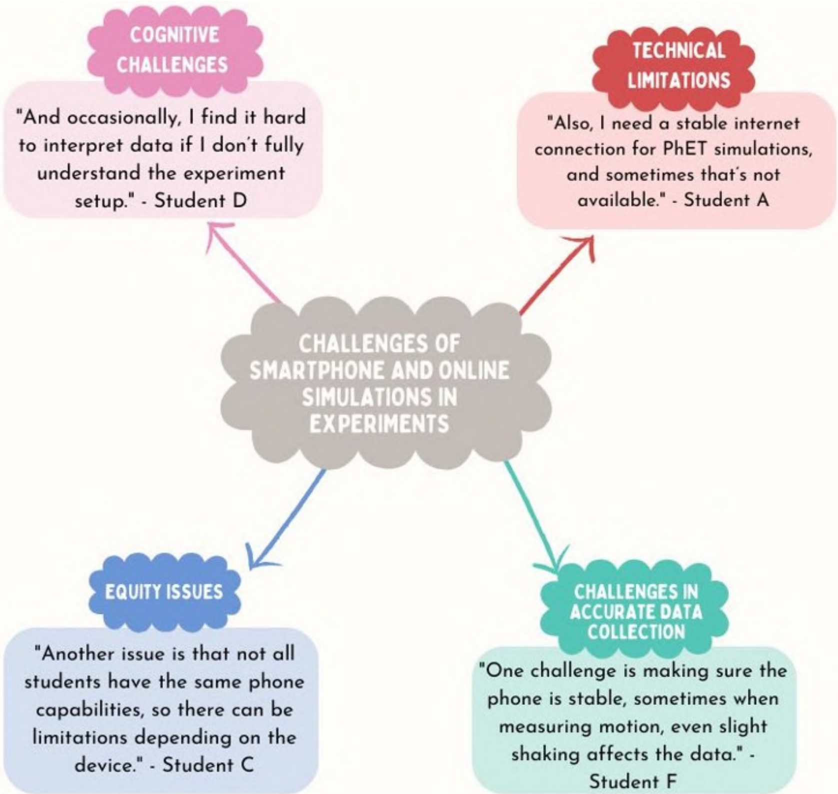


**Figure 4:** The challenges narrated by the students were related to cognitive challenges, technical limitations, equity issues, and challenges in accurate data collection.

The first challenge the students claimed is related to cognitive abilities. They talked about the difficulty of interpreting the data without prior knowledge of what the data is all about. The students in this case study were guided about the experiments they performed. They explored how to calculate constants like coefficient of friction, acceleration due to gravity, etc. They also verified the relationship between scientific constructs, such as magnetic flux density and current. As student D said, "And occasionally, I find it hard to interpret data if I don't fully understand the experiment setup". They were concerned primarily about future experiments or other students in another school who might not know the meaning of the data they were collecting. Students can also be battling with the correct sensor or online simulation to use or which section of the app to use if they are first-time users.

Apart from cognitive challenges, the experiments using smartphones and online simulations may encounter technical limitations, such as internet connectivity issues or environmental disturbances. Online simulations may not function without an internet connection, which presents a significant challenge for low-budget schools. Student A stated, "Additionally, I need a stable internet connection for PhET simulations, and sometimes that's unavailable". There are also setup parameters within the simulation or smartphone application that must be adhered to, which creates a technical hurdle for students. Student C noted, "Moreover, some apps require permissions or settings that can be confusing at first".

The technical challenge can affect the accuracy of the data gathered. For instance, when using an acoustic stopwatch to measure free fall time, the environment should be noise-free, and the smartphone should be as close to the falling body as possible. If the values are not gathered with precision and accuracy, the value of acceleration due to gravity could have higher uncertainty. Student F gave an example, "One challenge is making sure the phone is stable. Sometimes, when measuring motion, even slight shaking affects the data".

The last challenge is that not all phones can have similar sensors, which depends on the smartphone's brand and specifications. The general rule of thumb is that the higher the price of the smartphone, the more sensors are built in that can be used for classroom experiments. This has been noted by students

**Figure 5:** This setup was used to measure the time period of a pendulum and find acceleration due to gravity. To accurately measure the time period, the windows were closed to avoid interference.

whose smartphones vary from one another. Student A said, "Another issue is that not all students have the same phone capabilities, leading to limitations depending on the device". This can be exacerbated in remote areas where parents cannot afford to buy smartphones for themselves or their children. To solve this issue, teachers should be resourceful. They could organize a fundraising activity to finance the purchase of such technology. If the number of devices is limited, students can experiment in groups to foster collaborative learning skills.

The challenges mentioned above are common with emerging technologies. Environmental factors can affect the accuracy of collected data and illustrated how notifications from parents or friends can distract students [29]. Additionally, Pacala [30] emphasized that data accuracy can be problematic, especially for collections impacted by environmental factors such as the Earth's magnetic field and nearby appliances when measuring magnetic flux density. The cognitive challenges described by the students can be minimized or resolved through training similar to that conducted by the researcher before employing these teaching methods. Almarashdi and Saleh [26] argued that students can be trained so that, during classes, the teacher can focus on guiding them in exploring and verifying scientific principles. Furthermore, it is essential for teachers to receive training on these emerging technologies.

### 3.4. Limitations of the study

This study found limitations, while this paper offered valuable insights into the perceived benefits of the interventions utilized for the students. The study had only eight participants. This is relatively okay for data saturation in a case study, but the generalizability is limited only to the school where this study took place. Only those with informed consent were chosen as participants, which followed strict ethics. While this is correct, the paper recognised neglecting students with better experience in the intervention used. Finally, all interviews were in English, which the participants understood but may have lacked depth due to language proficiency.

## 4. Conclusion and prospect of future research

This research is a case study exploring students' lived experiences, perceptions, and feelings regarding the use of smartphones and online simulations in their physics lessons. By employing hermeneutic interpretation, structural analysis, and iteration, this paper successfully allowed themes to emerge from the transcripts. Following the research questions, three main themes surfaced as narrated by the participants. These themes include the benefits of smartphone-based experiments and online simulations, enhancing and complementing the role of digital tools in traditional hands-on experimentation, and the challenges associated with smartphone and online simulations in experiments.

The affordances included increased student engagement, practicality and accessibility of learning, connection to reality, and enhanced conceptual understanding. The students perceived the emerging technologies used by the researcher in physics lessons as complementary to traditional methods of conducting experiments and viewed them as flexible and efficient in collecting data. The complementary role of smartphones and online simulations to traditional experiment set-ups in experiments is unique in this paper and can be said to be the first time observed in a qualitative study. However, the challenges faced by the participants related to cognitive and technical limitations, equity issues, and the accuracy of the data gathered. It is recommended that experiments that require wind and noise-free conditions should be conducted in classrooms with closed windows to avoid interference.

Based on these themes, there is a need for intervention in the form of a professional development (PD) program for teachers on various emerging technologies, especially smartphone-based experiments. Teachers who have not been exposed to these technologies might be outmatched by teachers who have training in them. For equity, every teacher should be trained because smartphones are a teaching tool of the future. Along with teacher training, students should also receive complimentary training on the smartphone application or online simulation so the lesson can be smooth sailing.

Although this paper succeeded in its objectives, its generalizability is limited to the students and school where the research occurred. Therefore, a more extensive study is needed to encompass students in an entire region or country. To supplement the PD program, schools should consider formulating a smartphone policy for the classroom, as the OECD has highlighted its impact on students' scores in international exams. If smartphones significantly influence students' learning, this can also be examined in non-OECD countries. While this paper indicated that smartphone usage has a positive effect, its application in lessons was highly controlled and monitored. This could serve as a foundation for a smartphone policy, allowing usage only during smartphone-based experiments.

## Author contributions

All authors contributed equally in the article. All authors have read and agreed to the published version of the manuscript.

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This research did not receive external funding.

## Data availability statement

The data is kept confidential and stored in a safe storage. Only participants and their parents are allowed to view the content of the narratives.

## Conflicts of interest

The authors declare no conflict of interest.

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## Declaration on Generative AI

The authors utilized Grammarly for sentence coherence and correcting grammar.

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