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Virtual Physics Experiments: Transforming Science Process Skills Through Digital Integration

Syukriah[1]*, Evendi[2], Zainuddin[2], Muhammad Syukri[2], Tamil Selvan Subramaniam[3]

[1]Departement of Science Education, Postgraduate Program, Syiah Kuala University, Banda Aceh, Indonesia
[2]Departement of Physics Education, Faculty of Teacher Training and Education, Syiah Kuala University, Banda Aceh, Indonesia
[3]University Tun Hussein Onn, Johor, Malaysia

*Corresponding author's email: syukriahriaa@gmail.com

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Abstract. This research is motivated by the limited infrastructure of physics laboratories in educational institutions and students' science process skills (SPS) which are still in the low category. This study examines the effectiveness of implementing virtual laboratory-based worksheets in improving four main indicators of SPS: the ability to formulate problems, formulate hypotheses, identify variables, and design experiments. This study is a quasi-experimental study with a one-group pretest-posttest design involving 35 grade XI students of SMA Negeri 1 Kota Langsa. The research instrument is in the form of validated pretest and posttest questions, compiled based on the four indicators of SPS being studied. Data analysis uses the N-gain test to measure the increase in the ability of each indicator of SPS. The results of the study showed a significant increase in all indicators of SPS with N-gain values: identifying variables (0.92; high category), designing experiments (0.69; medium category), formulating problems (0.56; medium category), and formulating hypotheses (0.53; medium category). These findings confirm that virtual laboratory based worksheets are effective as an alternative to physics learning in developing students' SPS. This study recommends the implementation of virtual laboratories as an innovative solution to overcome the limitations of conventional laboratory facilities and support digital transformation in science education.
Keywords: Science process skills, virtual lab, worksheet physics learning, educational technology

Introduction

The transformation of global education towards the digital era has driven a paradigm shift in learning from conventional approaches to comprehensive technology integration (Antoninis et al., 2023). Recent research shows that the implementation of virtual technologies in science education has been shown to increase the effectiveness of learning and the accessibility of scientific experiments (Zhang & Liu., 2024). In Indonesia, the implementation of the independent curriculum emphasizes student-centered learning with high flexibility, where information and communication technology is a major factor in improving the quality of education (Kemendikbud RI., 2022). This context is in line with international research findings showing that technology integration in science learning can create significant opportunities to develop science process skills (SPS) through a more interactive and adaptive approach (Nirmala & Darmawati., 2021).

Modern physics learning faces major challenges in developing students' SPS. SPS are intellectual abilities that enable students to acquire knowledge through systematic scientific investigations (Hidah & Subdiyo., 2022). Contemporary studies confirm that virtual laboratories can effectively develop SPS by providing a safe and repeatable experimental environment (Potkonjak et al., 2016).These skills include the ability to formulate problems, formulate hypotheses, identify variables, design experiments, analyze data, and draw conclusions. However, the application of learning oriented towards the development of SPS still faces systematic obstacles in learning practices (Irwanto et al., 2018).

Limited laboratory facilities and infrastructure and access to practical equipment are significant obstacles in the development of SPS. The covid pandemic has accelerated the adoption of virtual technologies in education, with studies showing that virtual laboratories can maintain continuity of practical learning when access to physical laboratories is limited (Gamage et al., 2020). Empirical data shows that most educational institutions experience obstacles in implementing physics practicums due to limited time, facilities, and adequate laboratory equipment (Candra & Hidayati, 2020; Rini & Aldila., 2023). This condition has an impact on low student involvement in practical activities and a decrease in the quality of students' SPS development.

Based on the results of observations and initial interviews with physics teachers at SMA Negeri Kota Langsa, it is known that the curriculum currently being implemented is an independent curriculum with minimum completion criteria for physics learning of 78. The implementation of the ongoing practicum is still in the form of verification because it only proves concepts or principles that have been previously studied. The low level of students' SPS is identified from the inability of students to identify variables, lack of understanding of the use of practicum tools and how to operate them. Therefore, this study focuses on four indicators of fundamental SPS, namely formulating problems, formulating hypotheses, identifying variables, and designing experiments. Mastery of these four indicators will facilitate students in conducting experiments more effectively.

Virtual laboratories offer an innovative solution to overcome these limitations. These digital platforms allow students to conduct simulated experiments in a virtual environment that can enrich the learning experience with a wider and deeper variety of experiments (Teng & Wong., 2021; Erdem & Unal., 2021). Virtual experiments have the potential to overcome resource and environmental limitations in traditional physics learning (Wang et al., 2025). Students' SPS can improve as students practice more experiments (Hunegnaw et al., 2025). The integration of virtual laboratories into worksheets shows great potential in improving SPS effectively and efficiently (Sutarno et al., 2023).

Previous studies have shown the effectiveness of virtual laboratory-based worksheets in improving SPS (Ritmayanti & Supardi., 2017), facilitating practicums when tools and materials are limited (Sinta., 2022), and providing cost-effective learning (Syamsu & Ziraluo., 2022). Furthermore, virtual laboratory based worksheets have been proven to be practical and can replace direct practicums with significant improvements in learning outcomes (Aritonang., 2021; Halim et al., 2020). Although various recent studies have shown positive results, there has been no study that has examined in depth the four aspects of SPS specifically, namely formulating problems, formulating hypotheses, identifying variables, and designing experiments through the integration of digital learning in virtual physics experiments. This study aims to fill this gap by testing the effectiveness of virtual laboratory based worksheets in the context of physics learning that is oriented towards improving integrated SPS.

Methods

This study used a quasi-experimental method with a one-group pretest-posttest design. This design was chosen because it allows for measurement of changes in the dependent variable (SPS) before and after treatment (implementation of a virtual laboratory) was given to the research subjects. The population of this study was all students in classXI phase F SMAN 1 Kota Langsa which consists of 12 classes with a total of 430 students. The research sample was selected using purposive sampling technique with specific criteria, namely that students had not studied the material harmonic motionwhich is the focus of the virtual experiment, the class has adequate access to technology for the implementation of the virtual laboratory, and the subject teachers are willing to collaborate in the research. Based on these criteria, class XI-F6 with 35 students was selected as the research subjects. The research instrument consists of three main components that have been validated to ensure accurate measurement quality. The first instrument is a SPS test that is compiled based on four indicators of SPS, namely the ability to formulate problems, the ability to formulate hypotheses, the ability to identify variables, and the ability to design experiments. Furthermore, student and teacher response questionnaires to evaluate perceptions of the implementation of physics learning using virtual laboratory-based worksheets.

The research procedure was carried out systematically in five sequential stages. The first stage is the preparation stage which includes identifying learning problems, compiling research instruments, and validating instruments. The second stage is giving a pretest to measure students' SPS before being given treatment. The third stage is the treatment stage with the implementation of physics learning using virtual laboratory-based worksheets. The fourth stage is giving a posttest to measure students' SPS after treatment. The fifth stage is the evaluation stage which includes giving teacher and student response questionnaires and a comprehensive analysis of all research data.

The pretest and posttest data were analyzed using the N-gain test to determine the effectiveness of the treatment given. The gain score interpretation classification refers to Meltzer's (2002) categorization in Table 1.

Table 1. Indeks N-gain

Score Gain	Category
$g \geq 0.70$	High
$0.30 \leq g < 0.70$	Medium
$g < 0.30$	Low

(Source: Meltzer, 2002)

Student response questionnaires were constructed using Likert scales with four response alternatives: strongly agree (score 4), agree (score 3), disagree (score 2), and strongly disagree (score 1). Student response level calculations followed these steps:

1. Minimum score determination = minimum score × number of respondents
2. Maximum score determination = maximum score × number of respondents
3. Median calculation = (maximum score + minimum score) / 2
4. First quartile calculation = (minimum score + median) / 2
5. Third quartile calculation = (maximum score + median) / 2
6. The compilation of the interpretation scale based on the quartile distribution, can be seen in Figure 1.

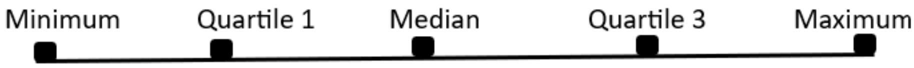

Figure 1. Interpretation scale based on quartile distribution

Student response questionnaire data were interpreted using categorization adapted from Yusrizal., (2016) in Table 2.

Table 2. Student response interpretation

Category	Index
Very positive	81.25 – 100
Positive	62.5 – 81.24
Negative	43.75 – 62.4
Very negative	25 – 43.74

(Source: Yusrizal, 2016)

Results and Discussion

Measurement of students' SPS is assessed using questions pretest-posttest regarding harmonic motion material. The data obtained from the implementation of the pretest and posttest were then analyzed comprehensively to evaluate the effectiveness of the virtual laboratory in learning to improve students' SPS on the indicators of formulating problems, formulating hypotheses, identifying variables, and designing experiments. When reviewed based on the average valuepretest and posttest each indicator can be seen in Figure 2.

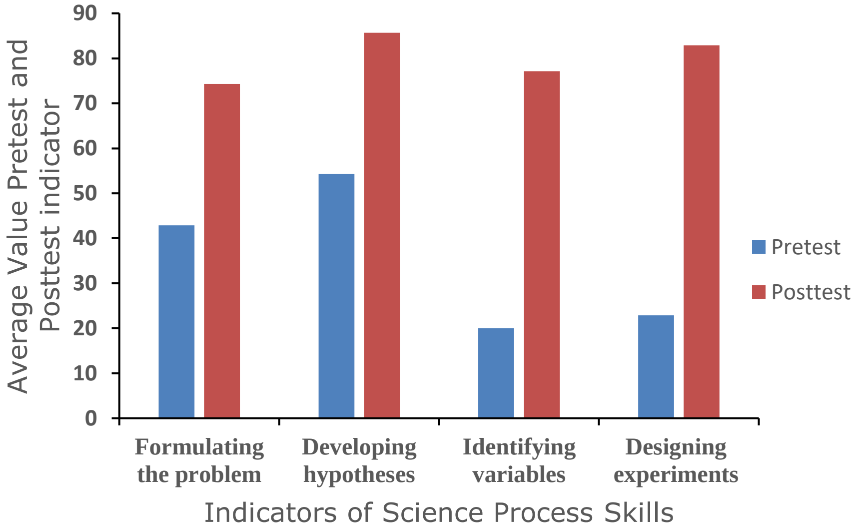

Figure 2. Average pretest and posttest scores by indicator

Based on data analysis shown in Figure 2, all four SPS aspects demonstrated significant improvement after implementing virtual lab-based worksheet in physics learning. Final test results showed consistent improvement in posttest results indicating higher achievement compared to students' initial conditions. To obtain a more comprehensive overview of learning effectiveness, N-gain analysis was conducted for each SPS indicator. This analysis aimed to specifically identify improvement levels achieved by students in each skill indicator, providing more detailed information about aspects experiencing the most significant improvement.

N-gain value distribution for the four SPS indicators is visualized in Figure 3, presenting learning effectiveness level comparisons for each measured skill component.

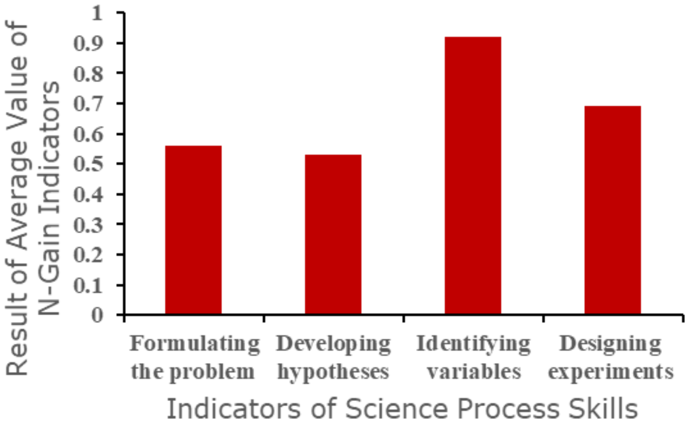

Figure 3. Average N-gain values by indicator

Based on the N-gain analysis in Figure 3, the four indicators of SPS, namely formulating problems, formulating hypotheses, identifying variables, and designing experiments, showed varying levels of improvement after the implementation of virtual physics experiments. Each indicator can be analyzed as follows:

1) Formulating the Problem

The The problem formulation indicator achieved an N-gain value of 0.56, which is categorized as a moderate increase. During the virtual laboratory session, students were systematically trained to identify and formulate scientific problems through a structured digital interface. Based on Bloom's theory (1956), the ability to formulate problems is included in the high-level cognitive domain that involves the process of analysis and evaluation. In the context of SPS, formulating problems requires the ability to analyze phenomena, identify relevant variables, and evaluate possible causal relationships (Anderson & Krathwohl., 2001). The development of problem formulation skills is essential for students' academic and professional success, as it supports their ability to address complex problems in various disciplines, including physics (Rodriguez et al., 2021). The virtual environment provides scaffolding support that allows students to recognize patterns and formulate meaningful research questions based on observed phenomena. As stated by Putra et al., (2021), virtual laboratories function as meaningful and logical learning so that students are able to take numerical measurements and evaluate the processes being explored, process and interpret data through intensive discussions, students will be able to write formulas for formulating basic laws of physics independently.

The cognitive theory developed by Sweller (1988) also explains why virtual laboratories are effective in developing problem-solving skills. Virtual environments can reduce extraneous cognitive load by providing a structured and intuitive interface, allowing students to focus on the high-level thinking processes required to formulate scientific problems (Chandler & Sweller., 1991). Virtual laboratories can reduce unnecessary cognitive load by providing an intuitive display, allowing students to focus on important concepts rather than navigating complex systems (Murtianto et al., 2022).

Virtual laboratories offer a controlled environment in which students can systematically manipulate variables, leading to more precise problem-solving skills. Moderate achievement on this indicator reflects the complexity of developing critical thinking skills necessary for effective scientific inquiry. Students demonstrate an increased capacity to distinguish between observable phenomena and underlying scientific questions through repeated exposure to virtual experimental scenarios. This is in line with research conducted by Ritmayanti & Supardi., (2017) showing that students' SPS improved after virtual lab-based worksheets were tested. The ability of digital platforms to present multiple experimental contexts simultaneously enhances students' pattern recognition abilities, which are fundamental to effective problem solving in scientific investigations.

2) Hypothesis Construction

Hypothesis generation indicators showed substantial improvement with an N-gain of 0.53, indicating moderate to high effectiveness. Virtual physics experiments provide students with direct access to theoretical frameworks and data visualization tools that support the logical reasoning process essential for hypothesis construction. The digital environment allows students to explore cause-and-effect relationships through interactive simulations before committing to a specific hypothesis. This exploration phase, facilitated by virtual lab tools, allows students to test initial ideas and refine theoretical predictions based on patterns observed in the simulation data. The integration of virtual labs into worksheets shows great potential in enhancing SPS effectively and efficiently (Sutarno et al., 2023; Wang & Li., 2024).

Discovery learning theory developed by Bruner (1961) is particularly relevant to the process of hypothesis generation in virtual laboratories. Bruner argued that students learn most effectively when they are actively engaged in the process of knowledge discovery. The virtual environment facilitates safe and controlled exploration, allowing students to develop hypotheses based on direct observations of simulated phenomena (Joyce et al., 2011). This exploration phase, facilitated by virtual laboratory tools, allows students to test initial ideas and refine theoretical predictions based on patterns observed in simulated data.

Virtual experiments enhance hypothesis development by providing comprehensive background information and real time feedback mechanisms. The ability to manipulate virtual parameters and observe direct consequences allows students to develop a complex understanding of variable relationships, leading to more precise and testable hypotheses. This is in line with multimedia learning theory which suggests that the combination of text and visuals can reduce students' cognitive load and help them assimilate information more effectively (Sutarno et al., 2023).

3) Variable Identification

Identifying variables showed the highest improvement among all indicators, achieving an N-gain of 0.92 which is categorized as high effectiveness which is in line with the findings of Geringer et al., (2024) who reported that virtual environments facilitate variable manipulation and visualization. Virtual laboratory environments provide exceptional support for these skills through interactive variable manipulation interfaces that clearly distinguish between independent, dependent, and control variables. Digital simulations offer immediate visual feedback as students modify different parameters, allowing them to understand the functional relationships between variables more clearly than traditional laboratory settings. The capacity of virtual environments to isolate specific variables while holding constant conditions for other variables provides students with a clearer conceptual understanding of the principles of experimental design.

The virtual laboratory digital interface has proven to be highly effective in teaching students variable identification. Cognitive load theory by Sweller (1988) provides an explanation for why the digital interface of virtual laboratories is so effective in teaching variable identification. By providing organized and intuitive visual representations, virtual laboratories reduce the intrinsic cognitive load associated with identifying and understanding relationships between variables. This allows students to allocate more cognitive capacity to higher-level processing (Chandler & Sweller., 1991). High achievement on this indicator reflects the strength of virtual laboratories in providing controlled experimental conditions in which students can systematically explore variable relationships without the constraints of physical equipment limitations. The ability of digital interfaces to highlight variable changes through color coding, graphical representations, and numeric displays significantly enhances students' analytical abilities. The use of virtual labs is very helpful in practical activities as stated by Indriastuti et al., (2017) who stated that interactive demonstration activities are needed so that students can identify variables so that they can design experiments.

4) Experimental Design

Experimental Designing experiments showed a significant improvement with an N-gain of 0.69, indicating moderate effectiveness. Virtual physics experiments allowed students to efficiently design and execute multiple experimental protocols, providing an opportunity to compare different methodological approaches and evaluate their relative effectiveness. The virtual environment offered students access to sophisticated measurement tools and data collection systems that would be challenging to implement in a traditional laboratory setting. This technological support allowed students to focus on the conceptual aspects of experimental design rather than the technical limitations of physical equipment. Students demonstrated an increased understanding of experimental controls, sampling procedures, and data collection strategies through repeated engagement with virtual experimental scenarios.

SPS can be trained by student gain direct experience during the learning process (Rinarta)et al., 2014). SPS involve cognitive or intellectual, manual, and social skills. Cognitive or intellectual skills by doing process skills students use their minds, manual skills are involved in the use of tools and materials, measurement, arrangement or assembly of tools, social skills mean that with process skills students interact with each other in carrying out teaching and learning activities (Makransky et al., 2019; Rustaman., 2005). Active student involvement in learning leads to increased SPS, with students moving from the "skilled" to "highly skilled" category (Hayati & Ami., 2022). The results of the student response questionnaire evaluation can be seen in Figure 4.

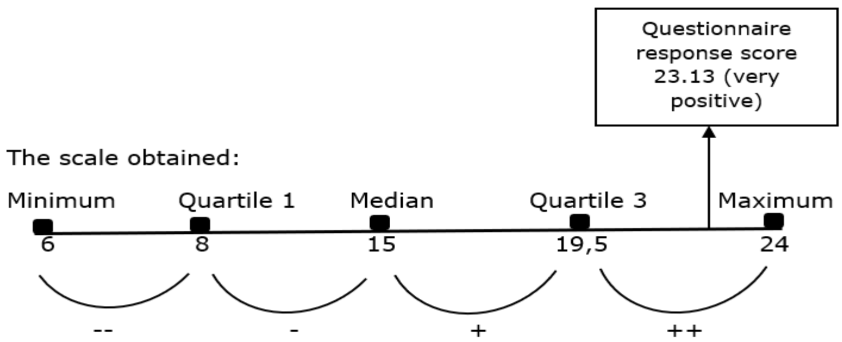

Figure 4. Student response questionnaire evaluation results

Quantitative analysis of student responses revealed very positive attitudes toward the virtual physics experiment, with a composite score of 23.13, indicating very positive acceptance. Students expressed particular enthusiasm for the interactive features of the virtual laboratory and its capacity to visualize abstract physics concepts through dynamic simulations. Qualitative feedback indicated that students appreciated the flexibility of the virtual experiment, which allowed them to repeat procedures, modify parameters, and explore alternative approaches without resource constraints. The ability of the digital platform to provide immediate feedback and guided instruction was highly valued by students who needed additional support in developing scientific reasoning skills.

The implementation of virtual physics experiments shows significant potential for enhancing SPS through digital integration. The technology's capacity to provide a controlled, repeatable, and highly interactive experimental environment overcomes many of the limitations of traditional laboratory instruction while maintaining the essential elements of scientific inquiry. Virtual laboratories offer a particular advantage in developing variable identification skills, as demonstrated by the highest N-gain values on this indicator. The digital environment's capacity to provide immediate visual feedback and systematic manipulation of variables supports conceptual understanding that may be challenging to achieve through traditional methods alone.

The moderate gains observed in the formulating problems and formulating hypotheses indicators suggest that these higher-order thinking skills require continued practice and may benefit from a hybrid approach that combines virtual and physical laboratory experiences. Integrating virtual tools with traditional instruction can optimize learning outcomes by leveraging the strengths of both approaches.

Based on the explanation above, it can be said that virtual lab based worksheets can make students more actively involved during the learning process. So that through this virtual lab-based worksheet, students are expected to be able to develop their abilities to be better, such as improving students' SPS in formulating problems, formulating hypotheses, identifying variables, and designing experiments. In accordance with the theory which states that students who use virtual laboratory-based worksheet media can understand the material taught better and are exciting and fun because students carry out experiments directly and the atmosphere created due to the interactive virtual practicum (Mahardika et al., 2022). This results in learning activities carried out by students becoming more meaningful and able to improve student understanding.

During the learning activities, students explore everything they get during the experimental process so that they can understand the harmonic motion material easily based on the concepts they find in the experimental activities, so that their SPS will also increase. This is in accordance with the statement by Sutarno (2023) that the integration of virtual labs in worksheets shows great potential in improving SPS effectively and efficiently.

When students design and conduct scientific investigations, they are able to develop skills such as: systematic observation, making careful measurements, and identifying and controlling variables. Interpretive skills are seen when students conduct observational investigations on experimental objects. Students will explain based on what they observe, and as they develop cognitive skills, they will be able to distinguish between explanations and research and be able to construct relationships based on evidence and logical arguments. This is in line with research conducted by Martinez & Singh. (2024) which states that the superiority of virtual laboratories in developing the ability to identify variables can be explained through their ability to provide clear visual representations of the relationships between variables. The digital interface allows students to manipulate one variable while observing changes in another variable in real-time, creating a more concrete understanding of the concepts of independent, dependent, and control variables.

The theoretical basis of this research uses the constructivist theory developed by Piaget and Vygotsky. According to Piaget (1977), learning is an active process in which students construct knowledge through interaction with the environment. Recent research by Muller et al. (2023) confirms that Piaget's constructivist approach in science education remains relevant, with an emphasis on the importance of hands-on exploration in building conceptual understanding. In the context of physics education, this theory emphasizes the importance of direct experience and exploration to develop deep conceptual understanding. Vygotsky (1978) through his theoryzone of proximal development the ZPD (zone of developmental perspective) explains that optimal learning occurs when students work in the area between actual and potential abilities with the help of scaffolding. Virtual laboratories provide digital scaffolding that allows students to explore complex physics concepts in a gradual and systematic manner. Virtual laboratories provide digital scaffolding that allows students to explore complex physics concepts in a step by step and systematic manner (Korlat et al., 2024; Yang et al., 2024).

This study was conducted at a single educational institution, which may limit the generalizability of the findings across diverse educational contexts. Future research should examine the effectiveness of virtual physics experiments at multiple institutions with varying technological infrastructures and student populations.Implementation of virtual laboratories for the sustainability of higher education requires consideration of specific institutional contexts (Zhang et al., 2024).While the study focused on four specific science process skills, future investigations could explore the impact of virtual laboratories on additional required competencies.

Several obstacles encountered during the research included students' confusion in following the learning steps due to their unfamiliarity with the applied method. Furthermore, this study had limitations, such as the lack of in-depth interviews with students to further evaluate the implementation of inquiry learning related to their abilities to observe, identify variables, and define variables. Learning analytics in virtual laboratories is crucial for understanding students' learning processes more deeply (Elmoazen et al., 2023). This study was also conducted in only one school, so the results might be more comprehensive if conducted in multiple schools. A systematic literature review by Wang et al. (2024) shows that virtual experiments in physics education require more comprehensive evaluation to measure their overall effectiveness.

Conclusion

This study demonstrates that virtual laboratory-based worksheets effectively improve students' SPS in physics learning. The use of virtual laboratories overcomes the limitations of physical facilities and successfully improves the ability to formulate problems, formulate hypotheses, identify variables, and design experiments. Therefore, virtual laboratory integration can be an alternative solution for developing SPS in schools with limited facilities.

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