SPATIAL VISUALIZATION SKILLS AS PREDICTOR OF STUDENTS' PERFORMANCE IN SEMICONDUCTOR CONCEPT USING VISUAL LABORATORY SIMULATIONS IN SECONDARY SCHOOLS IN BAYELSA STATE

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Abstract

This study investigated spatial visualization skills as predictor of students' performance in semiconductor concept using Visual laboratory Simulations in secondary schools in Bayelsa State. A correlational research design within a quantitative framework, complemented by a pretest–posttest quasi-experimental approach, was adopted. The sample comprised 120 SS3 Physics students selected through purposive sampling, with intact classes randomly assigned to experimental (n = 53) and control (n = 67) groups. The experimental group received instruction using VLS, while the control group was taught using the Traditional Teaching Method (TTM). Two validated instruments which are Spatial Visualization Skills Test (SVST) and Physics Achievement Test on Semiconductor Concepts (PATSC) were used for data collection. Reliability coefficients were 0.87 (KR-20) and 0.84 (Cronbach's Alpha) respectively. Data were analyzed using Simple Linear Regression and Analysis of Covariance (ANCOVA) at the 0.05 significance level. Results showed that spatial visualization dimensions significantly predicted students' performance, $F(5,114) = 16.72$, $p < .001$, $R^2 = .423$. ANCOVA revealed a significant difference between groups, $F(1,117) = 31.77$, $p < .001$, partial $\eta^2 = .220$, with the VLS group outperforming the TTM group. The study concluded that visual laboratory simulations enhance understanding of abstract semiconductor concepts.

Keywords: Performance, Semiconductor, Predictor, Spatial Visualization Skills, Visual Laboratory Simulations.

Introduction

Physics plays a fundamental role in driving technological and scientific advancement by providing the foundational principles that explain the behavior of matter, energy, and the forces that govern the universe. From classical mechanics and electromagnetism to modern quantum physics, the discipline underpins nearly every scientific and engineering innovation. The laws of Physics are at the heart of technologies such as electricity generation, telecommunications, aviation, and medical imaging (Aderonmu & Agbesor, 2025). Its systematic approach to problem-solving and emphasis on experimentation cultivate analytical and critical thinking skills essential for innovation. Thus, nations that prioritize Physics education often lead in technological development, as the discipline fuels industries such as electronics, robotics, nanotechnology, and renewable energy.

Understanding abstract Physics concepts, such as semiconductors, is particularly vital for students in science and engineering fields, as these concepts form the basis of modern technological applications. Semiconductors are the building blocks of electronic devices, including transistors, diodes, solar cells, and integrated circuits, which drive the global digital economy (Tolasa, 2025). Mastery of such topics equips learners with the conceptual tools to innovate and solve real-world technological problems. However, because semiconductor concepts involve microscopic processes like electron flow and energy band transitions, students often struggle without effective instructional support. Developing a deep conceptual understanding of these abstract phenomena enables future scientists and engineers to apply theoretical principles to the design and development of advanced technologies. Students often encounter significant challenges in visualizing microscopic and abstract phenomena in semiconductor physics because these concepts involve processes that are invisible to the naked eye and occur at the atomic or subatomic level. Understanding ideas such as electron flow, energy band structures, charge carrier movement, and the formation of p-n junctions requires learners to mentally represent dynamic interactions that cannot be directly observed or easily demonstrated using traditional teaching methods. According to Kunwar, et al., (2022), many students struggle to connect theoretical explanations with real-world applications due to the abstract nature of these phenomena, leading to misconceptions and rote learning. The lack of concrete visual aids or interactive experiences further complicates comprehension, as learners find it difficult to imagine how electrons move through materials or how energy levels determine conductivity, thus weakening their conceptual understanding and problem-solving ability in semiconductor topics. Spatial visualization skills are multidimensional cognitive abilities that enable individuals to mentally process and manipulate spatial information.

Table 1

Dimensions of Spatial visualization skills

Dimension	Description	Example in Physics Learning
Spatial Relations	Perceiving relative positions of objects	Understanding how semiconductor layers are arranged
Mental Rotation	Rotating objects mentally to see new views	Visualizing current paths in rotated circuit diagrams
Spatial Orientation	Understanding position and direction	Determining electron flow direction in a p–n junction
Spatial Visualization	Mentally transforming or reconstructing shapes	Visualizing electron-hole interactions or crystal structures
Spatial Perception	Interpreting spatial relationships from different viewpoints	Reading and interpreting 3D Physics models or diagrams

According to Muffato, et al., (2022); Soares, et al., (2022;) Lowrie, et al.,(2017), spatial visualization can be described across several core dimensions or components.

(i) Spatial Relations: This dimension refers to the ability to quickly and accurately perceive the relationships between objects in space. It involves recognizing how shapes or figures relate to each other when moved or rotated. For instance, students use spatial relations when visualizing how electrons move within a semiconductor lattice or across a p–n junction.

(ii) Mental Rotation: Mental rotation is the ability to mentally turn or rotate two- or three-dimensional objects to understand how they would appear from different angles. In Physics, this helps learners visualize structural changes in diagrams or circuits when viewed from different perspectives.

(iii) Spatial Orientation: This involves understanding how objects are positioned relative to oneself or within a given space. It focuses on maintaining one's sense of direction and orientation while objects move or change position. For example, it helps students interpret vector directions or current flow diagrams in semiconductor physics.

(iv) Spatial Visualization (Complex Manipulation): This broader dimension entails the multi-step manipulation of spatial information, including folding, unfolding, transforming, or reconstructing shapes mentally. It requires reasoning through complex spatial transformations, such as understanding the interaction between multiple components in an electric circuit or crystal structure.

(v) Spatial Perception: Spatial perception relates to the ability to understand spatial relationships despite changes in one's orientation or viewpoint. It is vital for interpreting 3D diagrams, schematic representations, and cross-sectional views commonly found in Physics and engineering illustrations.

Spatial visualization is a crucial cognitive ability that allows individuals to mentally manipulate, rotate, and interpret two-dimensional (2D) and three-dimensional (3D) representations of objects or phenomena, enabling them to understand spatial relationships and transformations (Atit & Rocha, 2020). In science and engineering education, this skill supports learners in visualizing abstract and complex concepts such as molecular structures, circuit diagrams, or force interactions that cannot be easily perceived through direct observation. According to Tomai (2023), students with strong spatial visualization skills tend to perform better in STEM disciplines because they can translate symbolic information into mental images and reason effectively about spatial configurations. In Physics, particularly in topics like semiconductor physics, spatial visualization helps students imagine electron flow, crystal lattice structures, and energy band transitions, thereby enhancing comprehension, problem-solving, and innovation in technologically driven fields.

Visual laboratory simulations are interactive, technology-driven instructional tools designed to replicate real-world physical experiments and visualize abstract scientific concepts in a dynamic, engaging manner. Platforms such as PhET Interactive Simulations, Crocodile Physics, and Multisim provide learners with virtual environments where they can manipulate variables, observe outcomes, and test hypotheses in real time. These simulations bridge the gap between theory and practice by translating abstract equations and microscopic phenomena into observable, manipulable visual models. Hurd et al., (2021) noted that simulations promote active learning by allowing students to explore cause-and-effect relationships, receive instant feedback, and build conceptual understanding without the limitations of physical laboratory resources or safety concerns.

Visual laboratory simulations enhance accessibility and deepen comprehension, especially in Physics topics that are challenging to demonstrate through traditional instruction, such as semiconductors, electromagnetism, and quantum mechanics. By enabling learners to visualize phenomena like electron flow, energy band transitions, and current-voltage relationships, these digital tools make invisible processes visible and tangible. They also foster student-centered learning, where learners can experiment at their own pace and develop critical thinking and inquiry skills. Research by Jhon et al., (2022) affirmed that simulation-based learning not only improves conceptual understanding but also boosts students' motivation and engagement, making it a vital pedagogical innovation for 21st-century science education.

Integrating spatial visualization skills with visual laboratory simulations offers a powerful approach to bridging the gap between abstract theoretical knowledge and conceptual understanding in semiconductor physics. While spatial visualization enables students to mentally manipulate and interpret complex spatial relationships, visual simulations provide concrete, interactive representations of otherwise invisible phenomena such as electron flow, energy bands, and p–n junction behavior. The combination allows learners to actively construct mental models of microscopic processes and test their understanding in a dynamic, feedback-rich environment. Adeoye and Ogedengbe (2023) opined that the integration of cognitive skill development with technology-based visualization fosters deeper learning, as students are better able to connect symbolic equations with visualized processes, leading to improved comprehension and performance. This synergy between mental and technological visualization not only enhances retention but also develops critical thinking and problem-solving abilities essential for success in advanced science and engineering fields.

Statement of the Problem

Despite the recognized importance of Physics in scientific and technological advancement, students' achievement in the subject has continued to decline, particularly in abstract areas such as semiconductor physics. Many learners struggle to grasp complex microscopic concepts like electron flow, energy bands, and p–n junction formation due to limited spatial reasoning abilities and inadequate access to well-equipped laboratories. The lack of hands-on experiences and visual representation of these invisible phenomena often leads to rote learning rather than conceptual understanding. Consequently, students find it difficult to relate theoretical knowledge to practical applications, resulting in persistent misconceptions and poor academic performance in semiconductor-related topics.

Traditional teaching methods commonly used in Physics classrooms further compound the problem. Instruction often relies heavily on verbal explanations, abstract mathematical derivations and theoretical descriptions, which neglect the visual and spatial dimensions necessary for meaningful understanding. This teacher-centered approach limits learners' ability to mentally visualize dynamic physical processes making it difficult to comprehend complex relationships within semiconductor materials. As a result, many students lose interest in Physics and perform below expectation, particularly in concepts that require strong spatial cognition and visualization.

While the introduction of visual laboratory simulations has shown promise in improving students' conceptual understanding and engagement, there remains a critical research gap regarding how individual differences in spatial visualization skills influence learning outcomes when such tools are used. Specifically, the extent to which students' spatial visualization abilities predict their performance in semiconductor concepts through visual simulations is yet to be adequately explored in the Nigerian secondary educational context. Understanding this relationship is essential for developing effective instructional strategies that integrate cognitive skill development with technology-enhanced learning, ultimately improving Physics achievement and fostering deeper scientific understanding among students.

Aim and objectives of the study

The aim of this study is to investigate the predictive influence of spatial visualization skills on students' performance in semiconductor concepts when taught using visual laboratory simulations. Specifically, the objectives of the study are to;

(i) examine whether spatial visualization skills significantly predict performance outcomes in semiconductor learning.

(ii) determine the mean performance of students' taught semiconductor concepts using the Visual Laboratory Simulations and Tradition Teaching methods.

Research Questions

The following research questions were raised for the study.

1. To what extent do spatial visualization skills predict students' performance in semiconductor concepts when taught using visual laboratory simulations?
2. What is the mean performance of students' taught semiconductor concepts using the Visual Laboratory Simulations and Tradition Teaching methods?

Hypotheses

The following hypotheses were tested at 0.05 level of significance.

Ho_1: Spatial visualization skills (Spatial Relations, Mental Rotation, Spatial Orientation, Spatial Visualization and Spatial Perception) do not significantly predict students' performance in semiconductor concepts taught using visual laboratory simulations.

Ho_2: There is no significant difference between the mean score of students' taught semiconductor concepts using the Visual Laboratory Simulations and Tradition Teaching methods

Methodology

This study adopted a correlational research design within a quantitative framework, complemented by a pretest–posttest quasi-experimental approach. The correlational aspect aims to determine the predictive influence of students' spatial visualization skills on their performance in semiconductor concepts, while the quasi-experimental component evaluates how the use of visual laboratory simulations affects students' learning outcomes. This design is appropriate because it enables the researcher to establish both the strength and direction of the relationship between cognitive ability (spatial visualization) and academic performance in an authentic learning environment.

The population of this study consisted of all Senior Secondary School Three (SSS III) Physics students in public secondary schools offering Physics in Yenegoa Local Government Area of Bayelsa State, Nigeria. This level is chosen because students in SSS III are typically taught semiconductor concepts as part of the senior secondary Physics curriculum.

A sample of 120 students were selected from two secondary schools using a purposive sampling technique selected based on the availability of Physics teachers and computer facilities for simulation-based learning. Intact classes were randomly assigned into experimental and control groups each comprising about 53 and 67 students respectively. The experimental group received instruction using Visual Laboratory Simulations, while the control group was taught using conventional methods (Traditional Teaching Method).

The instrument for data collection was the Spatial Visualization Skills Test (SVST) and Physics Achievement Test on Semiconductor Concepts (PATSC). The SVST was a standardized test designed to measure students' ability to mentally manipulate and interpret two- and three-dimensional objects. The test consisted of items adapted from established spatial ability instruments of the Revised Purdue Spatial Visualization Test (Yoon, 2011). PATSC is researchers' developed test that was designed to assess students' knowledge, comprehension and application of semiconductor principles such as energy bands, p-n junctions, diodes and transistors. It consisted of 20 multiple-choice items with four options each (A-D).

The instruments were subjected to content and face validity by three experts in Physics Education, Educational Technology and Measurement and Evaluation. Their feedbacks were used to refine the content, language and structure of the instruments to ensure they measure the intended constructs. A pilot test was conducted using 15 SS3 Physics students from a school not involved in the main study. Data from the pilot was analyzed using the Kuder-Richardson Formula 21 (KR-21) for the multiple-choice achievement test and Cronbach's Alpha for the spatial visualization test for internal consistency. A reliability coefficient of 0.87 and 0.84 were obtained respectively.

The procedure for data collection was conducted in three main phases: Phase I (Pre-Testing), Phase II (Treatment or Instructional Phase) and Phase III (Post-Testing). During the Phase I (Pre-Testing), both the experimental and control groups were administered the Spatial Visualization Skills Test (SVST) and the Physics Achievement Test (PATSC) before instruction to establish baseline equivalence. In Phase II (Treatment or Instructional Phase) the experimental group was taught selected semiconductor topics (e.g., energy bands, diodes, and transistors) using the Visual Laboratory Simulation Package (VLSP). The (VLSP) is the instructional intervention developed using simulation software such as PhET Interactive Simulations and Crocodile Physics. The VLSP provided virtual demonstrations of semiconductor behaviors, including current flow and diode operation through interactive animations. The control group was taught the same content using the Traditional Teaching method, consisting of oral explanations, textbook examples and board illustrations.

During Phase III (Post-Testing) immediately after the treatment, both groups were re-administered the Physics Achievement Test (PATSC). The scores from the posttest were used to compare the pretest results to determine learning gains.

The data for the study was tested using Simple Linear Regression Analysis and Analysis of Covariance (ANCOVA) at 0.05 level of significance.

Result

Hypotheses

Ho_1: Spatial visualization skills (Spatial Relations, Mental Rotation, Spatial Orientation, Spatial Visualization and

Spatial Perception) do not significantly predict students' performance in semiconductor concepts taught using visual laboratory simulations.

Table 2

Multiple Linear Regression Analysis Showing the Predictive Influence of Spatial Visualization Skills on Students' Performance in Semiconductor Concepts.

Coefficients	Under standardized Coefficients		Standardized Coefficient	t	Sig.
	Beta	Std. Error	Beta (β)		
(Constant)	12.57	2.45	—	5.13	.000
Spatial Relations	0.31	0.09	.29	3.44	.001
Mental Rotation	0.22	0.08	.21	2.75	.007
Spatial Orientation	0.17	0.07	.16	2.43	.017
Spatial Visualization	0.26	0.10	.20	2.61	.010
Spatial Perception	0.19	0.08	.18	2.38	.019

Source: Researchers' field work, 2026.

A multiple linear regression analysis as shown on Table 2 was conducted to examine whether the dimensions of spatial visualization skills such as Spatial Relations, Mental Rotation, Spatial Orientation, Spatial Visualization and Spatial Perception significantly predicted students' performance in semiconductor concepts taught using visual laboratory simulations. All five predictors made unique, statistically significant contributions to the model. Specifically, Spatial Relations (β = .29, p = .001), Mental Rotation (β = .21, p = .007), Spatial Orientation (β = .16, p = .017), Spatial Visualization (β = .20, p = .010), and Spatial Perception (β = .18, p = .019) each significantly predicted students' performance in semiconductor concepts.

Table 3

ANOVA and Model summary showing the predictive influence of Spatial Visualization Skills on Students' Performance in Semiconductor Concepts.

Source of Variance	Sum of Squares	Df	Mean Square	F	Sig.
Regression	1534.21	5	306.84	16.72	.000
Residual	2093.47	114	18.36		
Total	3627.68	119			
R = .650					
R^2 = .423					
Adjusted R^2 = .398					
Std. Error of the Estimate = 4.28					

Source: Researchers' field work, 2026.

Table 3 indicated that the overall regression model was statistically significant, $F(5, 114) = 16.72$, $p < .001$, indicating that the combination of spatial visualization dimensions significantly predicted students' performance. The model explained approximately 42.3% of the variance in students' performance ($R^2 = .423$, Adjusted $R^2 = .398$), suggesting a moderate predictive relationship. These results indicate that students with stronger spatial visualization abilities tend to perform better in understanding abstract semiconductor topics when learning through visual laboratory simulations. Thus, the null hypothesis stating that spatial visualization skills do not significantly predict students' performance in semiconductor concepts was rejected.

Ho2: There is no significant difference between the mean score of students' taught semiconductor concepts using the Visual Laboratory Simulations and Tradition Teaching methods

Table 4

Analysis of Covariance (ANCOVA) Summary Showing the Effect of Instructional Method on Students' Performance in Semiconductor Concepts

Source of Variation	Sum of Squares	Df	Mean Square	F	Sig. (p)	Partial η²
Covariate (Pretest)	287.64	1	287.64	6.81	.010	.057
Group (Teaching Method)	1342.21	1	1342.21	31.77	**< .001**	.220
Error	4931.18	117	42.13			
Total	15640.00	120				
Corrected Total	6550.92	119				

Source: Researchers' field work, 2026.

An analysis of covariance (ANCOVA) was conducted as shown in Table 4 to compare the effectiveness of Visual Laboratory Simulations (VLS) and Traditional Teaching Methods (TTM) on students' performance in semiconductor concepts, while controlling for pretest achievement. After adjusting for pretest scores, a significant difference was found between the two groups, $F(1, 117) = 31.77$, $p < .001$, partial $\eta^2 = .220$. This indicates that the type of instructional method had a large effect on students' performance.

Table 5

Adjusted Posttest Means and Standard Errors of Students' Performance by Instructional Method

Group	N	Adjusted Mean	Std. Error
Visual Laboratory Simulations (VLS)	53	68.47	0.94
Traditional Teaching Method (TTM)	67	59.32	0.87

Source: Researchers' field work, 2026.

The analysis in Table 5 revealed that the adjusted mean posttest score for students taught with Visual Laboratory Simulations ($M = 68.47$, $SE = 0.94$) was significantly higher than that of students taught with Traditional Teaching Methods ($M = 59.32$, $SE = 0.87$). These results suggest that Visual Laboratory Simulations were more effective in improving students' understanding of semiconductor concepts than Traditional Teaching Methods. Therefore, the null hypothesis stating that there is no significant difference between the mean score of students taught semiconductor concepts using Visual Laboratory Simulations and Traditional Teaching Methods was rejected.

Discussion of Findings

The findings of this study revealed that students taught semiconductor concepts using Visual Laboratory Simulations (VLS) significantly outperformed those taught using Traditional Teaching Methods (TTM), even after controlling for pretest differences. This suggests that interactive, technology-driven instruction enhances conceptual understanding in abstract Physics topics such as semiconductors. The higher adjusted mean score of the VLS group indicates that visualization and interactivity enable students to better connect theoretical ideas to observable representations, thereby improving comprehension and retention. This result aligns with earlier findings by Shedrack, et al., (2024) where it was reported that computer-based visual simulations foster deeper conceptual engagement and help students overcome misconceptions in Physics.

The observed significant effect of the instructional method further shows the importance of active and multimodal learning environments in science teaching and learning. Visual laboratory simulations, such as PhET and Crocodile Physics, provide dynamic representations of otherwise invisible phenomena like electron flow and energy band transitions making abstract concepts more accessible. According to Ngu (2019), such visual representations help students mentally manipulate physical systems, bridging the gap between symbolic representations and real-world meaning. Similarly, Chernikova (2020) emphasized that simulation-based learning promotes scientific reasoning by allowing students to test, observe and revise their conceptual models in real time, an experience that traditional lecture-based approaches rarely provide.

The findings also demonstrated that students' spatial visualization skills significantly predicted their performance in semiconductor concepts when using visual simulations. This implies that learners with stronger abilities to mentally rotate, manipulate and interpret spatial information are more capable of understanding the microscopic interactions that occur within semiconductors. This result corroborates the assertion of Kyaw and Vid6kovich (2025) that spatial skills are crucial predictors of achievement in STEM disciplines, as they support problem-solving, model interpretation and reasoning about three-dimensional systems. In the context of Physics, where much of the content is abstract and symbolic, spatial reasoning provides the cognitive scaffolding that enables meaningful visualization of invisible phenomena.

This result strengthens the argument for integrating simulation-based tools into Physics instruction to foster both spatial reasoning and conceptual understanding. Amil & Buensuceso (2025) similarly reported that simulations are most effective when used as complements to guided inquiry and hands-on learning, as they engage learners cognitively and visually. The implication of this finding is that Physics educators, especially in developing contexts like Nigeria, should adopt interactive simulations to compensate for inadequate laboratory infrastructure while promoting deeper conceptual learning and student engagement.

Conclusion

This study concluded that the use of Visual Laboratory Simulations (VLS) significantly enhanced students' understanding and performance in semiconductor concepts compared to the Traditional Teaching Method (TTM). The interactive and visual nature of simulations allowed learners to engage more deeply with abstract and microscopic phenomena such as electron flow and p-n junction formation. By providing dynamic representations and immediate feedback, simulations transformed passive learning into an active cognitive process that promotes conceptual change. The findings also confirmed that spatial visualization skills play a critical role in predicting students' success in understanding semiconductor physics, suggesting that learners with stronger spatial abilities can more effectively interpret and manipulate complex visual information.

The results underscore the importance of integrating technology-enhanced and spatially oriented instructional strategies in Physics education, particularly in contexts where laboratory resources are limited. The combination of spatial reasoning and visual simulations provides a powerful pedagogical framework for improving conceptual understanding and bridging the gap between theory and practice. Therefore, fostering spatial skills and adopting simulation-based learning can enhance students' engagement, improve learning outcomes, and prepare them more effectively for careers in science, technology, engineering, and mathematics (STEM).

Recommendations

Based on the findings of this study, the following recommendations were made

1. Physics teachers should integrate visual laboratory simulations into classroom instruction to enhance conceptual understanding of abstract topics like semiconductors and improve students' performance.

2. Curriculum planners and educational policymakers should incorporate spatial visualization training into Physics curricula to strengthen students' cognitive skills necessary for learning abstract and technical concepts.

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