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Unlocking the Potential of Python-Based Simulations: Understanding the Needs and Expectations of Future Physics Educators

Apit Fathurohman[1], Esti Susiloningsih[2*], and Hadi[3]
[1]Physics Education Study Program, Universitas Sriwijaya, Palembang, Indonesia
[2]Primary School Teacher Education Study Program, Universitas Sriwijaya, Palembang, Indonesia
[3]Physics Study Program, Universitas Sriwijaya, Palembang, Indonesia
*esti_susiloningih@fkip.unsri.ac.id

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Abstract
Teaching wave phenomena and optics remains challenging due to their abstract and highly visual nature. Pre-service physics teachers often struggle to form accurate mental representations, which hinders conceptual understanding. This study examined the needs, learning challenges, and expectations of future physics educators regarding Python-based simulations for learning optical waves to support conceptual understanding through dynamic visualization, interactive parameter exploration, and multiple representations of wave phenomena. A convergent parallel mixed-methods design was employed, integrating course-task analysis and a needs-assessment form with classroom observations and semi-structured interviews involving 60 third-semester physics education students at a state university in Indonesia. The novelty of this study lies in its integration of students' conceptual difficulties, technological readiness, and simulation expectations as a foundation for designing Python-based optical wave simulations tailored to physics teacher education. Quantitative findings showed that many students relied on procedural calculation without adequate conceptual explanation and experienced difficulties in interpreting interference and diffraction phenomena. Students strongly preferred dynamic visualizations and stepwise schematic explanations, while many also emphasized the importance of adjustable visual parameters and multiple representations in simulations. Qualitative findings highlighted expectations for slow-motion visualization, comparative parameter exploration, and introductory tutorial support. The study concludes that understanding students' perspectives is critical to designing effective educational simulations that enhance conceptual understanding and improve learning of abstract optical wave concepts.

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INTRODUCTION

The accelerated development of digital technologies has brought substantial changes to teaching and learning processes in the higher education (Akour & Alenezi, 2022; Alenezi et al., 2023; Bitar & Davidovich, 2024; Mohamed Hashim et al., 2022). In the context of physics education, this development brings specific challenges, as many physics concepts

are abstract, complex, and difficult for students to visualize and fully understand (Bouchée et al., 2023; Munfaridah et al., 2021; Subramaniam et al., 2025). Teaching approaches that rely heavily on lectures and static visual materials often contribute to cognitive overload and fail to support deep conceptual comprehension (Dervić et al., 2019; Hontarenko & Kovalenko, 2024; Rau, 2020; Skulmowski & Xu, 2022). The issue becomes more pronounced in teacher education programs, where prospective physics teachers are required not only to understand the content but also to develop the pedagogical ability to explain complex scientific ideas effectively to their future students (Bao & Koenig, 2019; Bouchée et al., 2023; Van Dusen et al., 2021).

Numerous studies emphasize the important role of visual representations and interactive learning tools in improving conceptual understanding, particularly in topics such as wave phenomena, optics, and interference patterns (Aregehagn et al., 2023; Banda & Nzabahimana, 2021; Munfaridah et al., 2021). For instance, a study by Srisawasdi & Kroothkeaw (2014) reported that students who used dynamic simulation tools showed better understanding of interference and diffraction concepts compared to those who learned using only static diagrams. These findings highlight the importance of incorporating computational simulations into physics instruction, especially for topics that require strong visualization and higher-level reasoning skills.

Well-known simulation platforms such as PhET Interactive Simulations and Physlets have been widely implemented in physics education and are proven to enhance conceptual understanding through interactive visualization and guided inquiry (Mohd Najib et al., 2022). Nevertheless, these platforms are generally developed as ready-to-use learning tools with predetermined structures, limited opportunities for parameter modification, and restricted access to the underlying computational models (Kitagawa et al., 2022). Although these characteristics are beneficial for introductory learning, they provide limited support for pre-service teachers who need to go beyond using simulations and develop an understanding of how physical models are constructed, how variables are mathematically related, and how representations can be adapted for instructional purposes. Prior studies have largely focused on the effectiveness of such simulations in improving student understanding but have not sufficiently explored how simulation environments can support deeper model construction and pedagogical design skills among future teachers.

In contrast, Python-based simulations offer a more flexible and generative learning environment (Vega & Cañas, 2019). Through Python, users are able to build physics models from the ground up, manipulate parameters more comprehensively, and design visualizations that align with specific learning goals or contextual needs (Savenko et al., 2024). This shifts the role of pre-service teachers from passive users of simulations to active developers of instructional media, promoting computational thinking, model-based reasoning, and stronger connections between mathematical formulations and physical interpretations. Despite these advantages, existing research has not yet clearly addressed how Python-based simulations can be systematically designed to support both conceptual understanding and pedagogical competence within teacher education contexts. This gap indicates a need for studies that integrate simulation design, conceptual learning, and pedagogical development into a unified framework.

However, the implementation of programming-based simulations, particularly those using Python, is still relatively limited in the pre-service physics teacher education (Lane et al., 2023). Several barriers have been identified, including limited coding proficiency, insufficient instructional guidance, and a lack of alignment between available digital tools and curriculum demands. Lamb et al. (2018) further emphasized that the effectiveness of simulation-based learning is highly dependent on interface clarity, the presence of appropriate scaffolding, and consistency with learning objectives. Without careful and

intentional design, Python-based simulations may impose excessive cognitive demands rather than support learning, thereby creating a gap between their theoretical potential and actual classroom application.

Previous studies on simulation-based physics learning have predominantly focused on evaluating the effectiveness of established simulation platforms and digital learning media. Although these studies have demonstrated positive impacts on conceptual understanding and student engagement, limited attention has been given to how pre-service physics teachers perceive and anticipate the use of Python-based simulations, particularly in wave phenomena and optics learning. Furthermore, prior research has rarely integrated students' conceptual difficulties, digital readiness, and learning expectations into the early stages of simulation design, resulting in a gap between technological development and pedagogical relevance.

To address this gap, the present study investigates the learning challenges, digital readiness, and expectations of pre-service physics teachers regarding Python-based simulations. Unlike previous studies that primarily treated simulations as instructional products to be evaluated, this study adopts a needs-driven and user-centered approach by positioning students' perspectives as the primary foundation for simulation design. The novelty of this study lies in its integration of conceptual difficulties, technological readiness, and user expectations to inform the development of pedagogically relevant simulation environments that support conceptual understanding, visualization of abstract phenomena, and pedagogical development. By systematically capturing these perspectives, this study aims to provide actionable guidance for the development of more adaptive, meaningful, and context-sensitive simulation tools. Accordingly, the study is guided by the following research questions:

RQ1. What conceptual difficulties do pre-service physics teachers encounter in learning wave and optics topics?
RQ2. What are their learning preferences and levels of familiarity with digital and simulation-based tools?
RQ3. What expectations and features do they consider important in Python-based simulations?
RQ4. How can these perspectives inform the design of pedagogically effective simulation tools?

METHODS

Research Design

This study adopted a mixed-methods design using a convergent parallel approach to investigate the needs, learning challenges, and expectations of pre-service physics teachers regarding Python-based simulations in learning optical wave concepts. Quantitative and qualitative data were collected concurrently and analyzed in an integrated manner to obtain a comprehensive understanding of participants' experiences.

The research procedure was conducted through several systematic stages. First, a needs analysis instrument was prepared, consisting of a structured questionnaire, classroom observation guidelines, and semi-structured interview protocols. Second, quantitative data were collected from students' course outputs and responses to the needs-assessment questionnaire, focusing on conceptual understanding, learning preferences, and familiarity with digital tools. Third, qualitative data were obtained through classroom observations to document learning behaviors, followed by semi-structured interviews with selected participants to gain deeper insights into their perspectives. Fourth, quantitative and qualitative data were analyzed separately using appropriate methods. Finally, the findings from both data sources were integrated to identify patterns, similarities, and differences,

leading to a comprehensive interpretation of the results. The overall sequence of these research activities is illustrated in Figure 1.

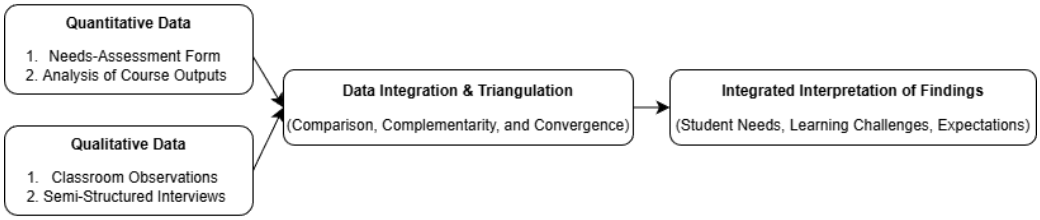

Figure 1 Sequence of mixed-methods data collection and integration in the study

Participants

The study involved 60 third-semester students from the Physics Education Study Program at Universitas Sriwijaya in the 2024/2025 academic year. These students were selected because they are entering intermediate coursework in physics and educational technology, making them an appropriate group for examining perceived needs and expectations regarding Python-based simulation tools. Their demographic characteristics are summarized in Table 1, which provides a more detailed breakdown across gender, age, academic background, and experience with programming and digital learning resources.

Table 1 Demographic profile of participants

Category	Subcategory	n	%
Gender	Female	55	91.7
	Male	5	8.3
Age	19 years	18	30.0
	20 years	32	53.3
	21 years	10	16.7
Prior programming experience	None	24	40.0
	Basic	30	50.0
	Intermediate	6	10.0
Experience with Python	Never used	27	45.0
	Introductory exposure	27	45.0
	Used in coursework	6	10.0

Data Collection Techniques

A range of data collection strategies was employed to obtain a holistic understanding of students' needs and expectations related to the use of Python-based simulations in physics learning. One primary source of data was students' coursework, including written explanations and problem-solving assignments from the Waves and Optics course. These artifacts were analyzed to identify common conceptual challenges, particularly in understanding interference and diffraction phenomena.

In addition, classroom observations were conducted to examine how students engaged during lectures, interacted with instructional materials, and responded to abstract representations of wave concepts. These observations provided insight into learning difficulties as they occurred in real instructional settings. To further enrich the data, a needs-assessment questionnaire was administered to capture students' learning preferences, their familiarity with digital tools, and their expectations regarding the integration of Python-based simulations in the course. The questionnaire included multiple-choice and semi-structured items, along with an open-ended question that allowed students to elaborate on their expectations for simulation-supported learning. The structure of this instrument is presented in Table 2, which details the assessed aspects and corresponding item distribution.

Table 2 Blueprint of the student needs-assessment form

No	Aspect Assessed	Item Numbers	Number of Items
1	Perceived learning challenges	1, 2, 3	3
2	Preferred learning media and explanatory formats	4, 5, 6, 7	4
3	Digital readiness & tool familiarity	8, 9, 10	3
4	Needs for python-based simulation support	11, 12	2
5	Desired functional characteristics of python simulations	13, 14	2
6	Additional expectations	15	1
	Total		**15**

The development of the needs-assessment instrument was grounded in a comprehensive review of literature on simulation-based learning in physics and the teaching of wave concepts. Its content validity was ensured through expert evaluation involving physics education scholars and instructional design specialists, who assessed each item in terms of clarity, relevance, and alignment with the intended constructs. Considering the exploratory focus of the study, reliability testing emphasized internal consistency at the construct level, with results indicating adequacy for descriptive and interpretive analysis rather than for statistical generalization.

Semi-structured interviews were carried out with a group of selected participants to gain deeper qualitative insights into their learning experiences. The interview guide explored students' perceived challenges in understanding optical wave concepts, their experiences with existing learning resources, and their expectations for the instructional use of Python-based simulations. The development of the interview protocol was aligned with the needs-assessment instrument to maintain consistency in the underlying constructs examined across both quantitative and qualitative data sources. To ensure the credibility of the qualitative data, the interview protocol was reviewed by experts to evaluate the clarity of the questions, the logical organization of thematic areas, and their alignment with the research objectives. An overview of the interview structure, including its main themes and guiding questions, is presented in Table 3.

Table 3 Blueprint of the student interview protocol

No	Aspect Explored	Guiding Focus
1	Background learning experiences in waves and optics	• Students' experiences during the course • Topics perceived as difficult or abstract • Situations where understanding felt limited (without diagnosing misconceptions) • Conditions that made content feel more accessible or more difficult
2	Situational challenges during learning activities	• Specific points in learning activities where students experienced confusion or uncertainty • Difficulties related to following explanations, connecting representations, or applying formulas • Types of support they felt were lacking during the learning process
3	Perceptions of current learning resources	• Materials and instructional approaches they frequently use • Aspects of current resources that help them learn • Gaps or limitations that make learning less effective from their perspective • Types of improvements they believe are needed
4	Experience with digital/simulation tools	• Previous exposure to digital tools in any subject • Ease or difficulty navigating and understanding simulations • Conditions under which digital tools previously felt helpful or unhelpful

No	Aspect Explored	Guiding Focus
		• Students' readiness and comfort level for using simulation-based learning
5	Needs and expectations for Python-based simulations	• What they hope Python-based simulations can help them visualize, understand, or explore • Types of representations (e.g., dynamic graphs, overlays, animations) they feel would support learning • Preferred modes of interaction, pacing, or guidance when using simulations • Suggestions for how simulations could be integrated into class or assignments
6	Additional needs not captured elsewhere	• Insights about learning needs beyond digital tools • Support mechanisms they believe would enhance their understanding (peer discussion, guided examples, step-by-step breakdowns, etc.) • Any expectations or concerns not covered in earlier questions

Data Analysis Techniques

The data obtained from multiple sources were analyzed using both qualitative and quantitative procedures in accordance with the characteristics of each dataset. Students' written tasks and course outputs were examined using qualitative content analysis to identify recurring patterns of conceptual difficulties, particularly in interpreting interference and diffraction phenomena. These difficulties were categorized into conceptual levels, including correct understanding, partial understanding, misconception, and lack of understanding, based on the accuracy and completeness of students' explanations in relation to established scientific concepts.

Classroom observation notes were analyzed to examine how these conceptual difficulties emerged during instructional activities. Observed behaviors were grouped into categories such as active engagement, passive participation, indicators of confusion, and expressions of misconception. The frequency and recurrence of these behaviors were used to support the interpretation of students' learning challenges. Responses from the needs-assessment questionnaire were analyzed descriptively using percentage distributions and presented in graphical form. Interpretation of the results was based on the relative dominance of response patterns, trends across items, and comparisons between categories rather than fixed numerical classification thresholds. Semi-closed responses were grouped according to response similarity to identify dominant tendencies. Open-ended responses were analyzed using inductive coding to extract recurring expectations regarding the features of Python-based simulations. The resulting codes were then organized into broader categories such as visualization needs, interactivity, usability, and instructional support. Interview data were transcribed and analyzed using thematic analysis involving open coding, axial coding, and selective coding to construct overarching themes.

To enhance the credibility of the findings, methodological triangulation was conducted by systematically comparing data obtained from questionnaires, classroom observations, students' written tasks, and semi-structured interviews. Quantitative findings from the questionnaire were first analyzed to identify dominant trends related to conceptual difficulties, digital readiness, and simulation preferences. These findings were then cross-checked with classroom observation data to examine whether similar patterns appeared during instructional activities and student interactions. Furthermore, interview data were used to provide deeper explanations and contextual clarification for the quantitative and observational findings. Data integration was conducted during the interpretation stage following the convergent parallel mixed-methods approach. Quantitative and qualitative

findings were initially analyzed separately and then compared across data sources to identify converging patterns, inconsistencies, and complementary insights. Converging findings were used to strengthen the validity of interpretations, while diverging findings were examined further to reveal contextual differences and alternative perspectives. The integrated analysis ultimately provided a comprehensive understanding of students' learning challenges, needs, and expectations regarding Python-based simulations in the Waves and Optics course.

RESULTS AND DISCUSSION

Students' Conceptual Challenges Reflected in Course Outputs

The analysis of students' submitted assignments and written outputs from the Waves and Optics course revealed several consistent patterns of conceptual difficulty. Overall, the findings indicate that many students demonstrate procedural competence without corresponding conceptual understanding, particularly when dealing with abstract wave phenomena. A summary of the key patterns identified from students' work is presented in Table 4.

Table 4 Patterns of conceptual difficulties identified from students' course outputs

Learning Context	Observed Difficulty	Evidence from Student Performance
Equation-based problem-solving	Reliance on procedural steps without conceptual explanation	70% of students correctly performed substitutions, whereas only 30% were able to provide a meaningful conceptual explanation of phase difference and amplitude
Interference representation	Difficulty interpreting diagram-based phase relationships	56% of students misidentified interference conditions in visual form, while 44% showed correct interpretation
Diffraction reasoning	Limited conceptual linkage between variables and observed patterns	63% applied formulas correctly but could not explain parameter effects, compared to 37% who demonstrated conceptual understanding
Problem transfer	Weak ability to apply concepts in unfamiliar situations	78% succeeded in routine problems, but only 22% demonstrated coherent reasoning in modified tasks, indicating a sharp decline in transfer performance

As shown in Table 4, a clear imbalance emerges between students' procedural proficiency and their conceptual understanding. While many students are able to carry out mathematical operations correctly, this ability is not consistently accompanied by a meaningful interpretation of underlying physical concepts. This pattern reflects a tendency to rely on formula-based reasoning without fully grasping the conceptual significance of wave properties.

Difficulties become more apparent when students are required to interpret visual and representational information. In particular, challenges arise when shifting from numerical representations to diagrammatic forms, indicating that students struggle to construct coherent mental models of wave interactions. Similar issues are observed in diffraction contexts, where the ability to apply formulas does not necessarily translate into an understanding of how physical parameters influence observable patterns. These trends suggest limited representational fluency, especially in coordinating multiple forms of representation within a unified conceptual framework.

The gap between surface-level understanding and deeper conceptual reasoning is further highlighted in transfer tasks. Students who perform adequately in familiar problem settings often encounter difficulty when faced with modified or less structured scenarios. This indicates that their knowledge remains context-dependent and lacks the flexibility required

for application in novel situations. Taken together, these findings point to the need for instructional approaches that move beyond procedural training toward fostering integrated conceptual understanding. In particular, learning environments should emphasize dynamic visualization, support the coordination of multiple representations, and encourage active exploration of underlying physical relationships. These insights also informed the subsequent phase of the study, which focused on examining students' needs and expectations regarding Python-based simulations.

The selection of Python as the basis for simulation development is grounded in both pedagogical and technological considerations. Pedagogically, Python-based simulations provide opportunities for students to engage with wave phenomena through dynamic visualization, real-time parameter manipulation, and the integration of graphical, mathematical, and conceptual representations within a single environment. Such features are particularly important for supporting conceptual reasoning in abstract topics such as interference and diffraction, where students often struggle to mentally connect equations with physical processes. In contrast to many existing simulation platforms that primarily offer fixed or ready-made interactive environments, Python enables greater flexibility for adapting simulations to specific instructional goals and students' learning needs.

From a technological perspective, Python offers advantages through its open-source ecosystem, accessibility, and extensibility. Libraries such as NumPy, Matplotlib, VPython, and Pygame allow simulations to be customized, modified, and expanded according to different learning contexts. Moreover, Python enables students not only to observe simulation outputs but also to gradually understand the computational logic underlying the models being represented. This capability is particularly relevant in physics teacher education, as it supports the development of both conceptual understanding and computational literacy. Consequently, Python-based simulations provide a more adaptable and pedagogically meaningful environment for bridging visualization, conceptual exploration, and computational engagement in wave and optics learning.

Observed Patterns in Classroom Engagement and Learning Behaviors

Classroom observations identified several recurring patterns in students' engagement with the learning process, especially when they were required to interpret abstract representations of optical wave phenomena. These observations offered valuable insights into the types of support students depended on, as well as the challenges that arose during instructional activities. An overview of the main interaction patterns observed in the classroom is presented in Figure 2.

Figure 2 Interaction dynamics observed during wave-based instruction

Several consistent patterns of classroom behavior were identified during the observations. Students tended to demonstrate increased attention and active participation when visual demonstrations were incorporated, such as ripple tank activities, laser-based

illustrations, and the use of simple physical analogies. These situations were often marked by immediate responses, including verbal reactions, nodding, or spontaneous questions, suggesting that concrete visual inputs played a key role in supporting their understanding. A contrasting pattern was observed when students engaged with static diagrams. Many of them repeatedly examined representations of interference patterns or wavefronts, often cross-referencing these visuals with their notes or discussing specific sections with peers. This repetitive interaction indicated that students required multiple opportunities to interpret and make sense of visual information before arriving at a stable understanding of wave relationships.

Moments of hesitation were also evident when students interacted with digital visualizations. Rather than directly exploring or modifying parameters, students frequently paused and waited for guidance from the instructor. This behavior pointed to difficulties in connecting the displayed simulations with the underlying physical concepts. In terms of interaction with the instructor, students were more inclined to ask questions during activities that involved hands-on engagement or stepwise visual processes. Conversely, during extended theoretical explanations, participation tended to decline, with students adopting a more passive role and fewer questions being raised. This pattern suggests that learning activities grounded in visual and experiential elements are more effective in sustaining student engagement. Overall, these observations emphasize the importance of continuous visual support and interactive representations in facilitating students' understanding of abstract optical wave concepts.

Insights From the Needs-Assessment Form

The needs-assessment form provides a nuanced portrait of how students navigate learning difficulties, engage with instructional media, perceive their own digital readiness, and articulate expectations for Python-based simulations. To avoid a rigid, repetitive presentation, each subsection below highlights distinct emphases drawn from the same instrument blueprint, with results conveyed through complementary visual representations. The initial set of questions examined which topics students perceived as most challenging in the Waves and Optics course. Students were asked to select the concepts they found most difficult rather than rate all topics equally. The response distribution is summarized in Figure 3.

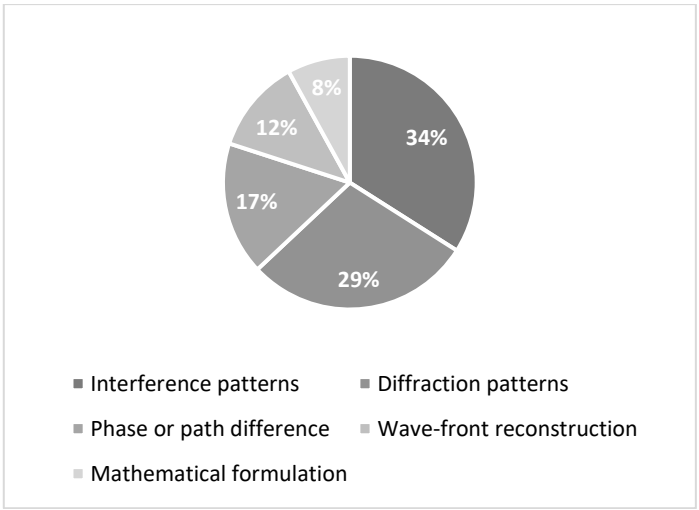

Figure 3 Distribution of perceived learning challenges

As illustrated in Figure 3, reported difficulties cluster around concepts that demand strong spatial and phase-based reasoning. Interference, diffraction, and phase relationships together dominate the response pattern, suggesting that many students struggle to mentally construct processes that cannot be observed directly. This concentration implies that effective simulations should prioritize dynamic and spatially explicit visualizations to render these abstract wave interactions more accessible. The second group of items explored the types of learning media students prefer when studying optical-wave phenomena. Because these questions compared relative preferences across formats, the findings are displayed in Figure 4.

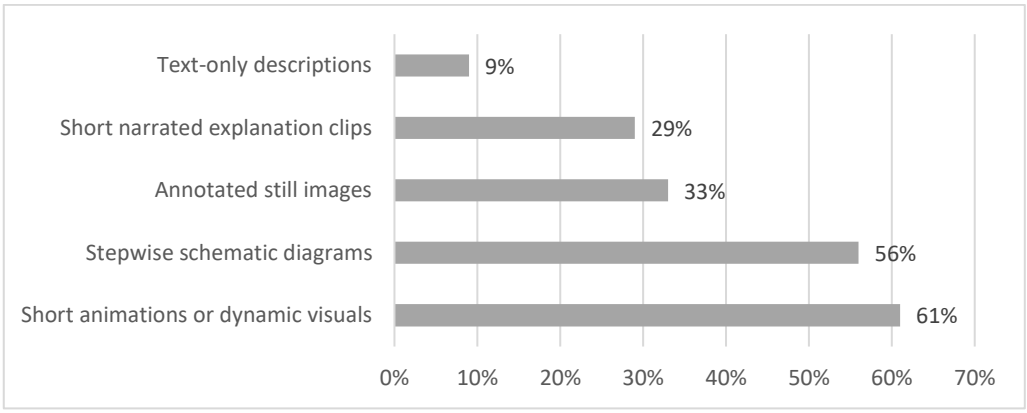

Figure 4 Preferred learning media and explanatory formats

Figure 4 reveals a pronounced inclination toward learning resources that integrate motion with sequential explanation. Animated representations accompanied by clear stages are rated highest, while narrated videos and annotated visuals play a complementary role. In contrast, text-only explanations receive minimal preference, underscoring a shift away from static descriptions toward multimodal representations for this content area. Students' readiness to engage with digital tools was addressed in the next section. This part of the instrument covered several interrelated competencies, making a consolidated visualization most appropriate, as shown in Figure 5.

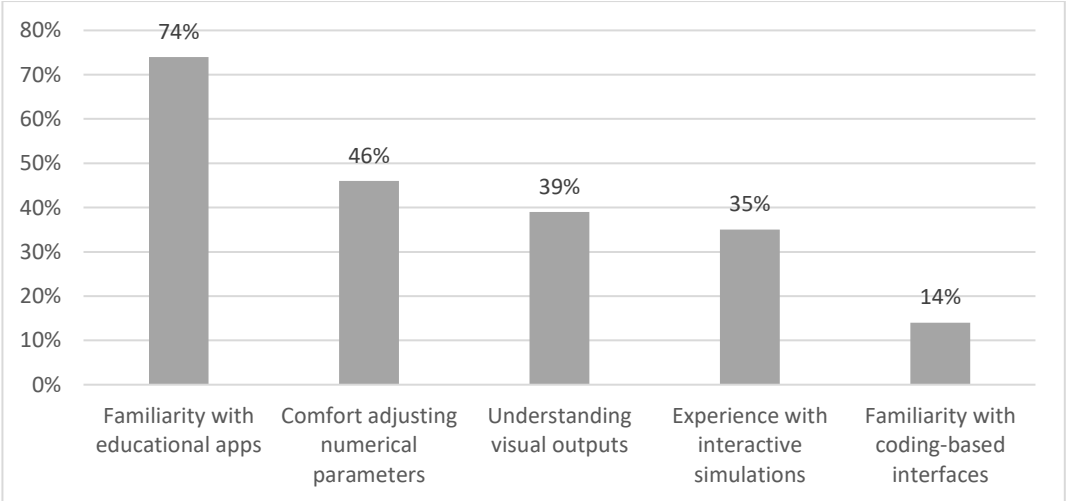

Figure 5 Digital readiness and tool familiarity

The pattern in Figure 5 indicates that although students are comfortable navigating app-based platforms and common digital interfaces, their confidence decreases markedly when simulations involve multiple adjustable parameters or links to underlying code. This disparity between general digital familiarity and simulation-specific competence highlights the need for intuitive interfaces and scaffolded interaction that gradually builds interpretive skill. Attention then shifted to students' perceptions of how necessary Python-based simulations are for the course. Given the limited number of broad response categories, the results are presented in Figure 6.

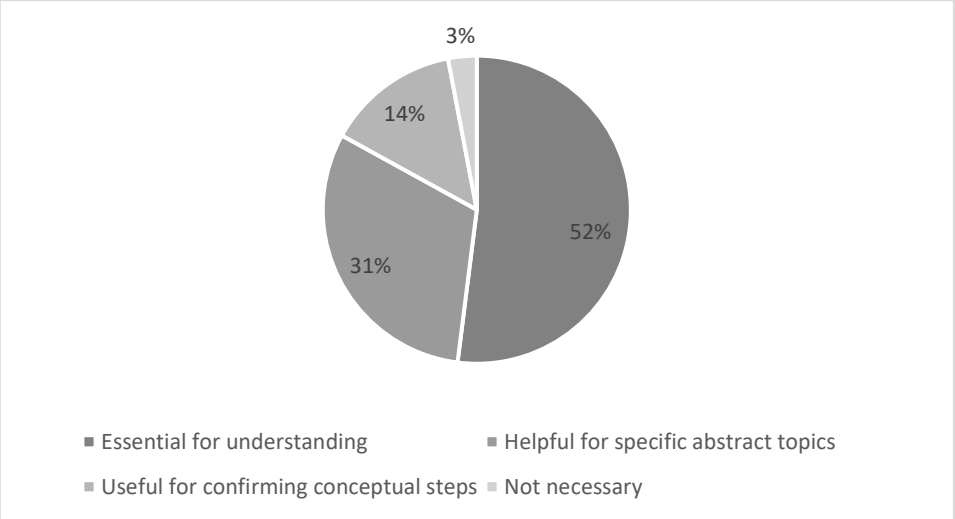

Figure 6 Student need for Python-based simulation support

As shown in Figure 6, a majority of students view simulations as indispensable for understanding wave-related optical concepts. Others regard simulations as particularly useful for highly abstract topics such as interference and diffraction, while only a small fraction consider them nonessential. Overall, these responses signal strong student endorsement of simulation-based support within the course. The following set of items focused on the specific features students expect from Python-based simulations. Because students could select multiple options reflecting different functional needs, the outcomes are visualized in Figure 7.

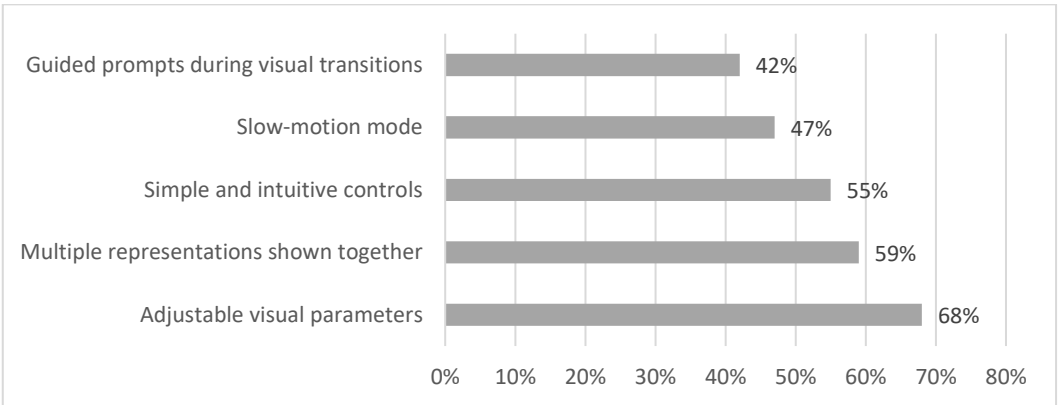

Figure 7 Desired functional characteristics of Python simulations

Figure 7 demonstrates that adaptability and clarity are central to student expectations. Adjustable visual parameters and multiple forms of representation emerge as priority features, while step-by-step interpretive prompts and slow-motion playback are seen as important enhancements that support deeper understanding rather than as standalone tools.

The final item of the questionnaire invited students to express, in an open-ended manner, the kinds of support they would expect from Python-based simulations for learning wave-based optical concepts. Their responses revealed clear expectations regarding how such simulations should facilitate understanding, particularly when dealing with abstract and dynamically changing phenomena. Many students emphasized the importance of controlling the pace of visual representations, explaining that rapid transitions often make the phenomena difficult to interpret. One student stated that the simulation should "display interference gradually so that the formation of bright and dark fringe patterns can be clearly observed," while another emphasized that "a slow-motion feature would be helpful so that the changes do not occur too quickly."

Expectations related to comparative exploration also emerged strongly, with students expressing the need to compare different parameter settings simultaneously. One respondent explained that "it would be easier to understand the effect of slit distance if the comparisons could be viewed directly without repeatedly changing the settings," while another added that "a comparison mode is important so that the differences in patterns can be observed more clearly." In addition, several students highlighted the importance of interpretive support during simulation exploration, such as concise explanatory prompts that appear when significant patterns emerge. One student noted that "there should be brief explanations when patterns begin to form, rather than only displaying moving images." Others emphasized the need for introductory guidance, suggesting that "a short tutorial at the beginning would help users avoid confusion when using the simulation for the first time." Taken together, these responses highlight students' expectations for simulations that are visually manageable, allow comparative exploration, and provide concise interpretive guidance. These findings offer meaningful direction for the development of Python-based simulation tools that are pedagogically relevant and supportive of conceptual understanding in wave and optics learning.

Taken together, trends across Figures 3 through 7 consistently indicate a strong demand for simulations that are visually transparent, adjustable in real time, and supported by incremental interpretive guidance. These preferences closely correspond to the conceptual challenges reported by students, providing coherent direction for the design of Python-based simulation tools in the Waves and Optics course.

Students' Voices from Semi-Structured Interviews

The semi-structured interviews provided deeper insight into how students perceived their learning experiences and why certain conceptual difficulties persisted during physics instruction. Many students explicitly described wave concepts as abstract and difficult to visualize, particularly when instruction relied primarily on static textbook images. One student explained, "I actually understand the formulas, but it is very difficult for me to mentally visualize the waves" (S07). Another student expressed a similar difficulty, stating, "When I only look at two-dimensional images, I cannot distinguish which parts are actually moving and which are merely representations" (S12). These accounts indicate that limited visualization contributes to persistent misconceptions and cognitive overload during learning.

Students also emphasized the need for more interactive and dynamic learning media. Several participants expressed a strong preference for tools that allow real-time manipulation and exploration. As one respondent stated, "If I can manipulate the simulation

myself, I understand the concept more quickly, especially when changes in frequency or amplitude can be observed directly" (S03). Another student added, "So far, we have only watched pre-made animations. It would be much better if we could explore the simulations directly, for example using a laptop" (S11). These statements reinforce the observed pattern that students value hands-on digital exploration rather than passive observation of animations.

A recurring theme that emerged from the interviews was students' limited readiness and familiarity with advanced digital tools, although most participants expressed willingness to learn if the tools could directly support their understanding. One student admitted, "I have never used Python before, but if there is guidance and the system is not too complicated, I would like to try it because it seems helpful" (S15). Another student shared, "Sometimes I hesitate to open additional applications, but if the results make the concepts clearer, I think it is worthwhile" (S02). These responses suggest that the main barrier is not resistance to technology, but rather limited prior exposure and lack of confidence in using unfamiliar digital tools.

Students were particularly enthusiastic about simulations that could simplify difficult visualizations through gradual and sequential representations. Several participants explained that observing wave interactions step by step would significantly improve their understanding. One student stated, "The most confusing part is interference. If there were a simulation that showed the process gradually, it would definitely be easier to understand" (S09). Another student agreed, explaining, "So far, the lecturer explains using static images. If a simulation could show the actual process, it would make much more sense" (S04). These comments highlight students' strong demand for customizable and sequential visualization features.

Beyond technical functionality, students also emphasized the importance of clarity, instructional guidance, and contextual relevance. Some participants believed that simulations should include concise explanations or prompts to guide exploration. As one student expressed, "Sometimes when I am given a simulation without guidance, I become confused about what I should focus on. There should probably be step-by-step instructions as well" (S06). Another student highlighted the importance of real-life applications, stating, "It would be helpful if there were examples of wave applications in everyday life so that I understand why I need to learn this topic" (S01). These reflections reveal students' expectations for learning experiences that are structured, meaningful, and contextually relevant.

Overall, the interview findings reinforce the earlier quantitative results by demonstrating that students experience persistent conceptual visualization difficulties, strongly prefer interactive digital media, and are open to using Python-based simulations as long as the tools are intuitive and supportive. Collectively, their perspectives underscore the urgent need for learning resources that are dynamic, manipulable, contextually grounded, and accompanied by clear instructional guidance.

In response to RQ1, the findings indicate that pre-service physics teachers experience substantial conceptual difficulties in learning wave and optics topics, particularly in visualizing abstract phenomena such as interference and diffraction. Data from questionnaires, classroom observations, and interviews consistently show that many students struggle to construct accurate mental representations when learning relies primarily on static textbook illustrations and lecture-slide diagrams. Students frequently reported difficulty distinguishing between symbolic representations and actual wave behavior, especially when interpreting interference patterns and wave propagation processes. These findings align with the study of Becker et al. (2020), which emphasized the role of dynamic visualization in reducing cognitive load and supporting conceptual

understanding. However, the present study extends this perspective by showing that conceptual difficulties are influenced not only by the absence of motion but also by limited opportunities for students to actively manipulate and explore visual representations. This finding suggests that learner interaction plays a critical role in supporting conceptual understanding in wave and optics learning.

With respect to RQ2, the findings reveal that students demonstrate strong preferences toward interactive digital learning environments, particularly simulations that allow real-time manipulation of parameters such as frequency, wavelength, and amplitude. Many participants expressed greater engagement with learning activities that support direct exploration rather than passive observation of animations. This finding supports previous research by McKagan et al. (2008), which showed that interactive simulations can improve conceptual understanding in physics learning. Nevertheless, the present study differs from earlier work because it specifically examines students' familiarity with and readiness toward Python-based simulations rather than widely available ready-made simulation platforms. The findings indicate that students are generally familiar with educational technologies and digital applications, yet many still feel uncertain when interacting with simulations involving multiple variables or computational processes. Similar to the findings reported by Mills et al. (2025), the results suggest that effective implementation of computational tools requires appropriate instructional support. However, this study further demonstrates that the main challenge lies in bridging the gap between surface-level digital familiarity and deeper computational understanding.

In relation to RQ3, the findings demonstrate that students expect Python-based simulations to provide not only dynamic visualization but also structured interpretive support and opportunities for comparative exploration. Many participants emphasized the importance of features such as slow-motion visualization, adjustable pacing, side-by-side parameter comparison, and concise explanatory prompts. Students also highlighted the need for introductory tutorials and guided instructions to help them navigate simulations effectively. These expectations indicate that students require simulations capable of supporting gradual conceptual construction rather than simply displaying animated phenomena. This finding reinforces the argument proposed by Cheung et al., (2019) that guided simulations are generally more effective than unguided exploration. However, the present study extends previous findings by identifying more specific forms of guidance expected by learners, including pacing control, step-by-step explanations, and contextual instructional support embedded within the visualization environment.

Finally, addressing RQ4, the findings provide important implications for the design of pedagogically effective simulation tools in physics education. The study demonstrates that effective Python-based simulations should integrate dynamic visualization, real-time manipulability, comparative exploration, gradual pacing, and structured interpretive guidance within a coherent instructional framework. These design elements are necessary not only to improve conceptual understanding but also to support students' engagement with computational thinking and digital exploration. Furthermore, the findings suggest that simulations should be designed as pedagogically meaningful learning environments rather than merely technological visualization tools. In this context, Python-based simulations have the potential to support both conceptual reasoning and pedagogical development among future physics teachers. Overall, the study contributes to simulation-based learning research by shifting the focus from evaluating technological effectiveness toward understanding user-centered design requirements that are context-sensitive, instructionally supportive, and aligned with students' learning needs in wave and optics education.

CONCLUSION

This study concludes that students encounter persistent conceptual difficulties when learning about waves and optics, particularly in interpreting interference, diffraction, and phase relationships. These challenges are closely associated with the abstract and highly representational nature of the content, which existing instructional approaches and materials do not always convey effectively. Findings from the needs-assessment and interview data indicate a strong preference for learning tools that are dynamic, manipulable, and visually intuitive. In this context, Python-based simulations that incorporate adjustable parameters, multiple representations, and embedded interpretive support show strong potential to enhance conceptual understanding and student engagement in wave-related topics. Based on these findings, the study recommends that the design and implementation of Python-based simulations prioritize features that directly address students' identified difficulties. For developers, this includes enabling adjustable pacing or slow-motion visualization to support careful observation, incorporating side-by-side parameter comparison to facilitate conceptual differentiation, and embedding concise interpretive prompts to guide attention during key transitions. For educators, such simulations should be integrated into structured instructional sequences rather than used as isolated tools, beginning with guided orientation and followed by activities that explicitly connect visual outputs with mathematical and conceptual representations.

Despite these contributions, several limitations should be acknowledged. The study was conducted within a specific cohort of pre-service physics teachers in a single institutional context, which may limit the generalizability of the findings to other educational settings or student populations. In addition, the reliance on self-reported data from questionnaires and interviews may introduce subjectivity, as responses reflect students' perceptions rather than direct measures of learning outcomes. Furthermore, this study focuses on needs analysis and exploratory insights rather than experimental validation, meaning that the actual impact of Python-based simulations on learning performance was not empirically tested. Future research is therefore recommended to extend these findings by implementing and evaluating Python-based simulation tools in diverse educational contexts, using experimental or quasi-experimental designs to measure their effectiveness. Further studies may also investigate how different levels of scaffolding and interaction design influence students' conceptual development and long-term retention, as well as how sustained exposure to simulation-based learning environments supports the growth of visualization and interpretive skills over time.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS STATEMENT

Conceptualization, AF and ES; methodology, AF and ES; formal analysis, AF; investigation, AF; data curation, AF; writing—original draft preparation, AF; writing—review and editing, ES and H; supervision, ES; validation, H; visualization, AF. All authors have read and agreed to the published version of the manuscript.

AI DISCLOSURE STATEMENT

The authors declare that this research was prepared, researched, written, and edited without the aid of artificial intelligence (AI) techniques.

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AUTHOR PROFILES

Apit Fathurohman
Apit Fathurohman is a lecturer in the Physics Education Study Program, Faculty of Teacher Training and Education, Universitas Sriwijaya, Indonesia. His research interests focus on physics education, educational technology integration, computational physics learning, and the development of simulation-based learning media.
Email: apit_fathurohman@fkip.unsri.ac.id
https://scholar.google.com/citations?user=kZvNrSoAAAAJ&hl=id&oi=ao
https://orcid.org/0000-0001-9377-1442

Esti Susiloningsih
Esti Susiloningsih is a lecturer in the Primary School Teacher Education Study Program, Faculty of Teacher Training and Education, Universitas Sriwijaya, Indonesia. Her research focuses on science education, innovative learning strategies, and the integration of digital technology in education to enhance students' conceptual understanding.
Email: esti_susiloningsih@fkip.unsri.ac.id
https://scholar.google.com/citations?user=kUkMo84AAAAJ&hl=id&oi=ao
https://orcid.org/0000-0002-8667-844X

Hadi
Hadi is a lecturer in the Physics Study Program, Faculty of Mathematics and Natural Sciences, Universitas Sriwijaya, Indonesia. His academic interests include theoretical physics, computational physics, and the application of physics concepts in scientific research and higher education.
Email: hadi@unsri.ac.id
https://scholar.google.com/citations?user=fIrNZYYAAAAJ&hl=id&oi=ao
https://orcid.org/0000-0003-4605-3864