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Exploring Preservice Science Teachers' Conceptual Understanding of Wave–Particle Duality through Prompt-Based Learning

Jadnika Dwi Rakhmawan Amrullah[1*], Nur Ahmad[1], Sri Rejeki Dwi Astuti[1], Firdha Yusmar[1], Ika Dewi Sumiati[1], Soraya Firdusi[1], Bartolomeus Kristi Brahmantia Putra[2], Israel Ametepey[3]
[1]Departement of Science Education, Faculty of Teacher Training and Education, Jember University, Indonesia
[2]Departement of Science Education, Faculty of Education, Ganesha University of Education, Indonesia
[3]Department of Science Education, Faculty of Science Education, Ghana
*Corresponding Author. Email: brontok26.fkip@mail.unej.ac.id

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Abstract: The study aimed to explore preservice science teachers' conceptual understanding of wave–particle duality and to examine the role of prompt-based learning in supporting conceptual change. A qualitative-dominant mixed-methods design was employed involving 32 preservice science teachers enrolled in a physics education course. Data were collected through pre- and post-instruction open-ended conceptual tasks and written responses to structured prompts during instruction. Quantitative analysis was used to identify trends in conceptual understanding, while qualitative thematic analysis examined the nature and development of participants' explanations. The results indicate that before instruction, most participants demonstrated classical or hybrid reasoning regarding wave–particle duality. After engaging in prompt-based learning, there was a significant increase in quantum-consistent conceptual understanding, accompanied by a shift from ontological to epistemic, model-based reasoning. Moreover, the findings reveal that explanation, reflective, and prediction–evaluation prompts played a key role in fostering conceptual coherence and metacognitive awareness, although some hybrid reasoning persisted. These results highlighted the potential of prompt-based learning as an effective instructional approach for supporting preservice science teachers' understanding of abstract quantum concepts.
Keywords: Prompt-based learning, wave–particle duality, preservice science teachers, conceptual understanding, quantum physics education.

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INTRODUCTION

The development of conceptual understanding in modern physics remains a persistent and well-documented challenge within science education research, particularly when instruction involves abstract and counterintuitive concepts rooted in quantum mechanics. Unlike classical physics, quantum phenomena require learners to abandon deterministic and tangible interpretations in favor of probabilistic and non-classical reasoning, which often conflicts with learners' prior knowledge and intuitive beliefs (Singh & Marshman, 2015; Krijtenburg-Lewerissa et al., 2017). One of the most conceptually demanding topics within this domain is wave–particle duality, a foundational principle that underpins learners' understanding of quantum behavior in electrons, photons, and other subatomic entities. Despite its central role, extensive research has shown that learners frequently struggle to develop a coherent and scientifically acceptable understanding of wave–particle duality, instead constructing fragmented, context-dependent, or mutually exclusive interpretations of wave and particle models (Baily & Finkelstein, 2015; McKagan et al., 2017).

Recent studies in physics education have demonstrated that students often interpret wave–particle duality through classical ontological categories, leading to misconceptions such as assuming particles alternate between wave-like and particle-like states or believing that wave and particle descriptions

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represent competing explanations rather than complementary models (Singh & Marshman, 2015; Kohnle et al., 2018). These conceptual difficulties are remarkably robust and persist across educational levels, including among undergraduate physics students and preservice science teachers (Didis, 2015; Krijtenburg-Lewerissa et al., 2019). The persistence of these misconceptions among preservice teachers is particularly problematic, as teachers' conceptual understanding strongly influences their instructional explanations, choice of representations, and responsiveness to students' ideas (Park et al., 2018; Kind, 2019). When preservice teachers hold unstable or fragmented conceptions of wave–particle duality, these ideas may be reproduced and reinforced in classroom practice, thereby perpetuating conceptual difficulties across generations of learners (Hake, 2017). Within the broader literature on science teacher education, conceptual understanding is widely understood as a critical component of pedagogical content knowledge. Teachers are expected not only to possess accurate scientific knowledge but also to understand the underlying conceptual structures that enable meaningful explanations and representations (Kind & Chan, 2019; Park & Chen, 2012). However, empirical evidence suggests that preservice science teachers often rely on procedural knowledge or formula-based reasoning when engaging with quantum concepts, with limited emphasis on conceptual coherence, epistemological reflection, or model-based reasoning (McKagan et al., 2020; Krijtenburg-Lewerissa et al., 2019). This pattern highlights a significant gap between curricular expectations and actual learning outcomes in teacher education programs, especially in modern physics topics.

To address these challenges, science education researchers have explored various instructional approaches designed to support conceptual understanding in quantum mechanics. These include inquiry-based learning, multiple representations, interactive simulations, model-based instruction, and conceptual change-oriented approaches (Wieman et al., 2018; Baily & Finkelstein, 2019; Kohnle & Passante, 2017). While such approaches have shown promise in improving engagement and learning outcomes, research indicates that learners often struggle to externalize their reasoning processes or critically evaluate their assumptions in engaging with abstract quantum phenomena (Vosniadou, 2019; Lombardi et al., 2016). Without explicit scaffolding, the targets learners' cognitive and metacognitive processes, instructional interventions may fail to promote deep, big, and durable conceptual change.

In this context, prompt-based learning has emerged as a promising pedagogical approach for supporting learners' conceptual reasoning (Putri & Kuswanto, 2021). Prompt-based learning involves the systematic use of structured prompts designed to elicit learners' explanations, predictions, justifications, and reflections, thereby making their thinking visible and open to revision (Aleven et al., 2016; Kang et al., 2021). Rather than providing direct explanations, prompts encourage learners to actively construct meaning, confront inconsistencies in their reasoning, and integrate new information with existing knowledge structures. From a theoretical perspective, prompt-based learning aligns closely with constructivist learning theories and contemporary models of conceptual change, which emphasize active engagement, metacognitive monitoring, and iterative refinement of ideas as central mechanisms of learning (Chi & Wylie, 2014; Sinatra et al., 2020).

Empirical research across science education contexts has demonstrated that prompts enhance explanatory quality, foster higher-order thinking, and support conceptual coherence, particularly when learners are required to articulate causal mechanisms and reflect on alternative explanations (Lombardi et al., 2016; D'Mello et al., 2018). In teacher education contexts, prompts have also been proven to support reflective thinking and professional reasoning by encouraging preservice teachers to examine their assumptions and connect theory with practice (van Velzen et al., 2017; Hsieh & Tsai, 2020). However, despite this growing body of research, relatively few studies have examined the application of prompt-based learning to quantum physics education, and even fewer have focused specifically on preservice science teachers' understanding of wave–particle duality (Utami et al., 2023; Yuliana & Suyanto, 2020).

The limited attention to prompt-based learning in quantum physics education represents a significant gap in the literature, especially the abstract nature of wave–particle duality and the well-documented persistence of misconceptions in this domain (Nurhayati et al., 2022). Existing studies on quantum education have primarily focused on the use of simulations, visualizations, or conceptual surveys to measure learning outcomes, with less emphasis on the cognitive processes through the construct and refine their conceptual explanations of learners (Kohnle et al., 2018; McKagan et al., 2020). Consequently, there is a need for research that explores, not only instructional interventions

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improving conceptual understanding but also how learners' ideas evolve when they are systematically guided through structured prompts.

The present study addresses this need by exploring preservice science teachers' conceptual understanding of wave–particle duality through prompt-based learning. Although previous studies in quantum physics education have widely examined students' misconceptions and the effectiveness of simulations, visualizations, and model-based instruction in supporting conceptual understanding, relatively little attention has been given to how structured prompt-based learning facilitates conceptual change in abstract quantum topics, particularly within teacher education contexts. Unlike earlier research that primarily evaluates learning outcomes through conceptual surveys or simulation-based interventions, the particular study investigates how explanation, reflective, and prediction–evaluation prompts function as cognitive scaffolds that support preservice teachers in restructuring their reasoning about wave–particle duality. Therefore, the novelty of this study lies in examining prompt-based learning, not only as an instructional strategy but also as a mechanism for promoting epistemic, model-based reasoning among preservice science teachers in quantum physics learning.

This study is significant because preservice science teachers' conceptual understanding directly influences how abstract quantum concepts are represented in future classroom instruction. Strengthening their epistemic understanding is essential for improving the quality of physics teaching and learning at the secondary school level. The significance of this work lies in its potential to contribute, both empirically and theoretically, to the field of science education. Empirically, the study provides insights into how preservice teachers engage with prompts and how their conceptual explanations develop over time. Theoretically, it contributes to ongoing discussions about the role of scaffolding and metacognition in conceptual change, particularly in the context of abstract scientific concepts. Despite the growing body of research on quantum physics education and prompt-based learning, there remains a notable gap in the literature.

Previous studies have primarily focused on the use of simulations, visualizations, and conceptual assessments to improve students' understanding of quantum concepts, with limited attention to how learners' reasoning processes evolve through structured cognitive scaffolding. In particular, no prior study has explicitly examined how prompt-based learning was used to explore and support preservice science teachers' reasoning about wave–particle duality as a model-based and epistemic construct.

Furthermore, existing research has not systematically investigated which specific features of prompts (e.g., explanation, reflection, prediction–evaluation, and cognitive conflict) contribute to conceptual change in quantum contexts. Addressing this gap is important, as preservice teachers' conceptual understanding plays a critical role in shaping future classroom instruction and students' scientific reasoning. From a practical perspective, the findings may inform the design of instructional interventions in teacher education programs that aim to support deeper conceptual understanding of modern physics topics. By focusing on preservice science teachers and employing prompt-based learning as an instructional lens, the study responds to calls for research that bridges learning sciences and disciplinary education research (Sinatra et al., 2020; Kind, 2019).

Based on the theoretical and empirical literature, this study adopted an exploratory perspective to investigate how preservice science teachers' conceptual understanding of wave–particle duality that develops through engagement with structured prompts. Rather than testing a predefined hypothesis, the study seeks to identify patterns of conceptual change and the instructional features supporting the development of quantum-consistent reasoning. Accordingly, the purpose of the study was to explore how preservice science teachers' conceptual understanding of wave–particle duality is articulated and refined when learning is supported by structured prompts. This research focuses on three key points:

1. How do preservice teachers conceptualize wave–particle duality prior to instruction supported by prompt-based learning?
2. How do preservice science teachers' conceptual explanations of wave–particle duality evolve when they engage with structured prompts?
3. What features of prompt-based learning cognitive demand support or constrain conceptual understanding of wave–particle duality among preservice science teachers?

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METHOD

The study employed a qualitative-dominant mixed-methods design. The integration of qualitative and quantitative followed a qualitative-dominant, embedded mixed-methods design. Qualitative analysis served as the primary approach to examine changes in conceptual explanations. Meanwhile, quantitative analysis was used to identify trends in the distribution of conceptual categories before and after instruction. The quantitative findings supported the interpretation of qualitative shifts in reasoning. And, it strengthened the overall validity of the conclusions, which used to investigate preservice science teachers' conceptual understanding of wave–particle duality through prompt-based learning. The qualitative component served as the primary strand to capture the nature and development of participants' conceptual explanations, while quantitative analysis was used to support interpretation and identify overall trends. The design was adapted from established mixed-methods frameworks in science education research, with modifications specific to quantum physics instruction.

Participants were preservice science teachers that enrolled in a physics education course at a Jember University. Purposive sampling was used to select participants who had completed classical physics courses but had not yet received formal instruction in quantum mechanics. This ensured comparable prior knowledge while allowing examination of early conceptual development related to wave–particle duality. Ethical approval was obtained, and all participants provided informed consent.

The study was conducted in three phases. The intervention was conducted over four instructional meetings within two weeks. Each meeting lasted approximately 100 minutes and focused on different aspects of wave–particle duality, including photon behavior, electron interference, and interpretation of the double-slit experiment. During the learning phase, participants responded to structured prompts, such as: "Explain why electrons produce an interference pattern in the double-slit experiment," "Predict what would happen if one slit is observed during measurement," and "Reflect on whether wave and particle descriptions represent physical reality or explanatory models." These prompts were designed to stimulate explanation, prediction, and reflection processes that support conceptual change.

1. Pre-instruction phase: Participants completed an open-ended conceptual task to elicit their initial understanding of wave–particle duality.
2. Prompt-based learning phase: Instruction incorporated structured prompts designed to elicit explanation, prediction, and reflection. The prompts were adapted from prior prompt-based learning studies, with contextual modifications related to quantum phenomena, such as photon behavior and the double-slit experiment.
3. Post-instruction phase: Participants completed a follow-up conceptual task parallel to the pre-instruction task and enabling systematic comparison of conceptual explanations across phases.

Data consisted of participants' written responses to pre- and post-instruction conceptual tasks and their written responses to prompts during instruction. All data were collected in written form to ensure consistency and facilitate systematic analysis.

Data analysis. Qualitative data were analyzed using Nvivo12, following iterative coding procedures to identify patterns and shifts in conceptual reasoning. Responses were categorized into conceptual levels (e.g., classical, hybrid, and quantum-consistent reasoning). To enhance reliability, coding was conducted independently by two researchers and refined through consensus. Quantitative analysis was conducted descriptively to support qualitative findings. The frequency of quantum-consistent explanations before and after instruction was compared using a Wilcoxon signed-rank test with a significance level at $p < 0.05$. For quantitative comparison, conceptual categories were converted into ordinal scores, representing levels of conceptual sophistication (classical = 1, hybrid = 2, quantum-consistent = 3). These scores allowed the use of paired-samples statistical comparison to examine changes in conceptual understanding before and after instruction.

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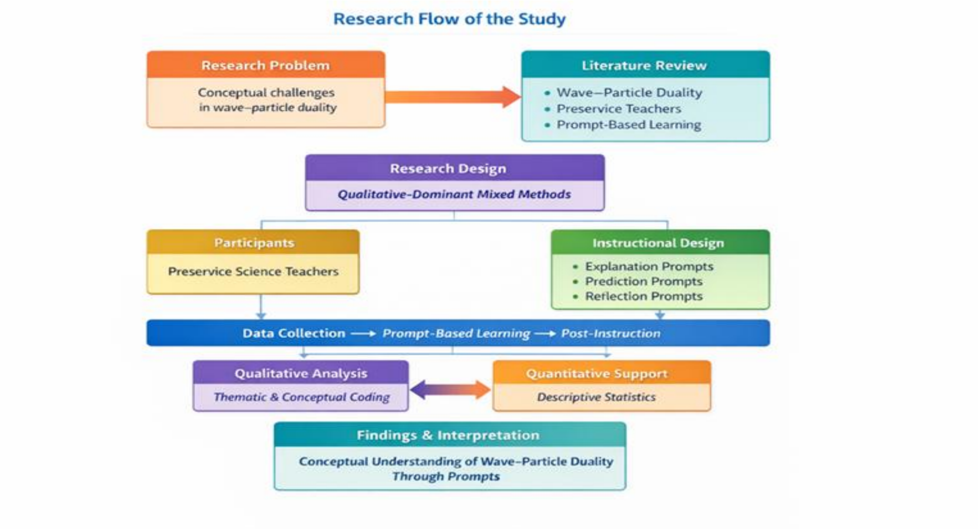

Figure1. Research Flow

RESULT AND DISCUSSION

This section presents the integrated quantitative and qualitative results of the study, organized according to the three research questions. Quantitative data are used to identify overall trends in conceptual understanding, while qualitative findings provide explanatory depth on the nature and development of preservice science teachers' reasoning.

RESULT

1. Preservice Science Teachers' Initial Conceptualization of Wave–Particle Duality

Quantitatif Result

Quantitative analysis of the pre-instruction conceptual task (N = 32) indicated that most preservice science teachers demonstrated non-quantum-consistent understanding of wave–particle duality. Only 18.75% (n = 6) of participants exhibited quantum-consistent reasoning, while the majority relied on classical or hybrid explanations.

Table 1. Distribution of Conceptual Understanding Before Instruction

Conceptual Category	n	Percentage (%)
Classical reasoning	14	43.75
Hybrid reasoning	12	37.5
Quantum-consistent reasoning	6	18.75
Total	**32**	**100**

These results indicate that 81.25% of participants relied on classical or fragmented reasoning at the outset of the study.

Qualitative Result

The qualitative findings indicate that preservice science teachers entered instruction with conceptions of wave–particle duality that were largely rooted in classical physics ontology. Analysis of pre-instruction written responses revealed that most participants interpreted duality as a literal physical transformation between wave and particle states, rather than as a model-based explanation of quantum phenomena.

Participants frequently employed deterministic language, suggesting that quantum entities possess definite forms changing according to experimental conditions. Only a small number of responses reflected an emerging understanding of duality as a complementary explanatory framework. These

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findings suggest that, before instruction, most preservice teachers had not yet developed epistemic awareness on the role of models in quantum physics.

This pattern is consistent with previous studies that learners often rely on classical ontological categories when reasoning about quantum phenomena, even at advanced levels of education. In the context of teacher education, the conceptions are particularly problematic, as they may be reproduced in future instructional explanations.

Table 2. Qualitative Themes of Initial Conceptual Understanding

No.	Conceptual Theme	Description of Reasoning	Representative Indicator	n
1	Classical ontology	Duality interpreted as physical change between wave and particle	"An electron becomes a wave when it passes the slit"	14
2	Hybrid reasoning	Partial combination of classical and quantum ideas	"Sometimes it is a wave, sometimes a particle"	12
3	Emerging complementary model	Duality understood as an explanatory model	"Wave and particle are ways to describe behavior"	6

The mix method - combined quantitative and qualitative - findings indicate that preservice science teachers entered instruction with conceptions of wave–particle duality that were largely inconsistent with accepted quantum interpretations. Quantitatively, more than four-fifths of participants demonstrated classical or hybrid reasoning before instruction. Qualitative analysis explains this pattern by revealing that participants predominantly interpreted duality as a literal physical transformation, relying on deterministic language, and classical ontological categories.

This convergence of data suggests that participants had not yet developed epistemic awareness of the role of models in quantum physics. Rather than viewing wave and particle descriptions as complementary representations, preservice teachers treated them as mutually exclusive physical states. These findings support previous research that classical intuitions are highly resistant to change and persist, even among advanced learners and preservice teachers. From a teacher education perspective, this conceptions are particularly problematic; these conceptions may influence how preservice teachers interpret and explain quantum concepts in instructional contexts.

1. **Changes In Conceptual Understanding After Prompt-Based Learning**

Quantitatif Result

Post-instruction quantitative results showed a substantial improvement in participants' conceptual understanding. The proportion of quantum-consistent responses increased to 56.25% (n = 18), while classical reasoning decreased to 15.63% (n = 5).

Table 3. Comparison of Conceptual Understanding Before and After Instruction

Conceptual Category	Pre (%)	Post (%)	Change (Δ)
Classical reasoning	43.75	15.63	−28.12
Hybrid reasoning	37.5	28.13	−9.37
Quantum-consistent reasoning	18.75	56.25	37.5

To examine the statistical significance of the improvement, a paired-samples t-test was used. The statistical comparison was based on ordinal conceptual scores derived from categorized responses rather than raw test scores. Therefore, the analysis should be interpreted as indicating trends in conceptual development rather than precise measurement of learning gains was conducted on quantum-consistent scores. The analysis revealed a significant increase following instruction ($t = 6.21$, $p < 0.001$), with a large effect size (Cohen's $d = 1.10$).

Qualitative Result

Post-instruction qualitative analysis revealed a substantial shift in participants' conceptual explanations. After engaging with prompt-based learning, many preservice teachers articulated wave–

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particle duality as a complementary and context-dependent model, rather than as a physical property of quantum objects.

Participants increasingly demonstrated epistemic awareness by acknowledging the limitations of classical models and emphasizing the role of measurement context. The use of probabilistic and model-oriented language became more frequent, indicating a deeper level of conceptual coherence. Importantly, several participants explicitly reflected on inconsistencies in their initial reasoning. It suggests that learning involved conceptual restructuring rather than surface-level correction.

One participant initially stated, “Electrons change into waves when passing through the slit,” but later revised the explanation to “Wave and particle descriptions are models used to explain different experimental results.” This shift illustrates the transition from ontological reasoning toward epistemic model-based understanding.

Despite these improvements, a small number of participants continued to display hybrid reasoning, indicating a conceptual change was gradual and different across individuals. This finding aligns with theoretical perspectives that view conceptual change in quantum physics as a non-linear and iterative process.

Table 4. Qualitative Themes of Post-Instruction Conceptual Understanding

No.	Conceptual Theme	Description of Reasoning	Representative Indicator	n
1	Complementary model	Duality described as complementary explanatory models	“Wave and particle are complementary models in quantum physics”	18
2	Epistemic awareness	Recognition of limits of classical physics	“Classical physics cannot explain all experimental results”	9
3	Residual hybrid reasoning	Persistent mixing of classical and quantum ideas	“The particle is probabilistic but still has a path”	5

The integrated results for RQ2 demonstrate that prompt-based learning supported indications of conceptual development toward more scientifically aligned explanations rather than surface-level improvement. Quantitatively, the proportion of quantum-consistent reasoning increased significantly after instruction, accompanied by a large effect size. Qualitatively, this improvement is explained by a shift in participants’ explanatory frameworks, from ontological interpretations toward epistemic, model-based reasoning.

Participants’ post-instruction responses increasingly emphasized on measurement context, probabilistic interpretation, and the limitations of classical models. Importantly, many participants explicitly reflected on inconsistencies in their initial explanations, indicating that prompts supported metacognitive engagement. However, the persistence of hybrid reasoning among a subset of participants suggests that conceptual change was gradual and non-linear. The finding is consistent with theoretical models of knowledge, restructuring in abstract scientific domains.

These findings extend and add prior research on quantum physics education by demonstrating that structured prompts—without reliance on simulations or laboratory interventions—can effectively support conceptual reorganization. Prompt-based learning appears to have a function by making learners’ reasoning explicit, creating cognitive conflict, and encouraging reflective revision of prior knowledge.

3. Features of Prompt-Based Learning that Support Conceptual Understanding Results

Quantitative Result

Quantitative analysis was conducted to examine preservice science teachers’ engagement with different features of prompt-based learning and their association with conceptual understanding of wave–particle duality. Data were derived from participants’ written responses during the instructional phase and coded based on the type of prompt engaged.

The results indicate variation in the frequency of participants engaged with different types of prompt. Explanation-oriented prompts were the most frequently engaged, followed by reflective and prediction–evaluation prompts.

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Table 5. Quantitative Distribution of Engagement with Prompt Types

Prompt Type	Number of Participants (n)	Percentage (%)
Explanation prompts	26	81.25
Reflective prompts	23	71.88
Prediction–evaluation prompts	19	59.38
Constraint-based prompts	17	53.13
Total participants	**32**	**100**

These data indicated more than three-quarters of participants actively engaged with prompts requiring explicit explanation of reasoning. Meanwhile, over half engaged with prompts designed to challenge classical interpretations.

Further quantitative analysis examined the relationship between engagement with prompt types and post-instruction conceptual understanding. Participants who engaged with two or more prompt types were more likely to demonstrate quantum-consistent reasoning in the post-test.

Table 6. Prompt Engagement and Post-Instruction Conceptual Understanding

Level of Prompt Engagement	Quantum-Consistent (n)	Non-Quantum (n)
High engagement (≥3 prompt types)	14	3
Moderate engagement (2 prompt types)	4	5
Low engagement (≤1 prompt type)	0	6

A chi-square test of independence indicated a significant association between the level of prompt engagement and post-instruction conceptual understanding ($\chi^2 = 9.84$, $p < 0.01$).

Qualitative Result

Qualitative analysis of preservice science teachers' written responses to instructional prompts revealed distinct patterns on how specific features of prompt-based learning supported or constrained conceptual understanding of wave–particle duality. The analysis focused on identifying recurring themes in participants' explanations, reflections, and revisions across learning tasks.

One prominent theme emerging from the data was the role of explanation prompts in encouraging participants to externalize their reasoning. When prompted used to justify their answers, participants were more likely to articulate underlying assumptions and reasoning pathways. This process often revealed inconsistencies between their initial explanations and accepted quantum interpretations, which creates opportunities for conceptual refinement.

A second supportive feature was the use of reflective prompts that explicitly asked participants to evaluate or reconsider their prior responses. These prompts encouraged metacognitive engagement, enabling participants to identify limitations in their earlier reasoning and to revise their conceptual frameworks accordingly. Several participants demonstrated increased awareness of the epistemic status of wave and particle descriptions after engaging with such prompts.

Prediction–evaluation prompts also played a critical role by introducing cognitive conflict. When participants were asked to predict outcomes of quantum experiments and subsequently compare those predictions with experimental results, discrepancies became apparent between expectation and observation. This mismatch prompted deeper reasoning and led some participants to abandon deterministic interpretations in favor of probabilistic, model-based explanations.

Despite the overall positive impact, qualitative data revealed constraints in the effectiveness of prompt-based learning. Some participants responded to prompts procedurally or superficially, providing brief or formulaic answers without engaging in deeper conceptual reasoning. In these cases, prompts functioned more as tasks to be completed rather than as catalysts for reflection.

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Another constraining factor was the persistence of hybrid reasoning, where participants integrated prompt-generated insights into existing classical frameworks without fully restructuring their understanding. These responses suggest that prompts solely may be insufficient for some learners, particularly when prior conceptions are strongly entrenched.

The integration of quantitative and qualitative data for RQ3 provides insight into how specific features of prompt-based learning, which contributed to conceptual development. Quantitative results showed that higher levels of engagement with multiple prompt types were significantly associated with quantum-consistent post-instruction understanding. Qualitative findings clarify this relationship by revealing explanation, reflective, and prediction–evaluation prompts that served distinct but complementary functions.

Explanation prompts encouraged participants to articulate and examine their reasoning, often revealing underlying assumptions rooted in classical physics. Reflective prompts promoted metacognitive awareness, enabling participants to evaluate the adequacy of their explanations and recognize conceptual limitations. Prediction–evaluation prompts introduced cognitive conflict by confronting participants' expectations with experimental outcomes, motivating deeper conceptual revision.

Nevertheless, qualitative data indicate that prompts were less effective when engagement are superficial or procedural. In such cases, participants incorporated new information into existing classical frameworks without fully restructuring their understanding. This finding suggests that prompt effectiveness depends not only on prompt design but also on sustained engagement and instructional support.

DISCUSSION

The findings provide important insights into how preservice science teachers conceptualize wave–particle duality and how prompt-based learning supports the development of more scientifically aligned understanding. The discussion is organized according to the three research questions and integrates quantitative trends and qualitative interpretations.

First, the results found out that before instruction, most preservice science teachers relied on classical or hybrid reasoning. It indicates limited understanding of wave–particle duality as a model-based concept. This finding is consistent with previous studies showing that learners tend to interpret quantum phenomena using classical ontological categories, often assuming that particles physically alternate between wave and particle states (Singh & Marshman, 2015; Krijtenburg-Lewerissa et al., 2019). The dominance of deterministic language and the interpretation of duality as a physical transformation suggest that participants had not yet developed epistemic awareness on the role of models in quantum physics.

From the perspective of conceptual change theory, these initial conceptions can be understood as deeply rooted prior knowledge structures that are resistant to change (Vosniadou, 2019). In particular, preservice teachers' reliance on classical ontology reflects a stable but scientifically inaccurate framework that constrains their ability to interpret quantum phenomena, especially critical in teacher education contexts because misconceptions may influence instructional practices and perpetuate students' misunderstandings.

Second, the results demonstrate that prompt-based learning supported a significant shift toward quantum-consistent conceptual understanding, as evidenced by both quantitative improvement and qualitative changes in reasoning. The substantial increase in quantum-consistent responses, accompanied by a large effect size, indicates that the intervention was effective in promoting conceptual development. More importantly, qualitative findings reveal that this improvement was not merely procedural but involved a transition from ontological reasoning to epistemic, model-based reasoning.

This shift aligns with constructivist learning theory, which posits that learners actively construct knowledge through interaction, reflection, and revision of prior ideas (Chi & Wylie, 2014). The use of structured prompts might have facilitating this process by making learners' thinking explicit and encouraging them to confront inconsistencies in their reasoning. In particular, participants' ability to recognize the limitations of classical explanations and adopt probabilistic interpretations reflects the development of metacognitive awareness, which is a key mechanism in conceptual change.

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However, the persistence of hybrid reasoning among some participants suggests that conceptual change is gradual and non-linear, rather than immediate and uniform. This finding supports existing literature that learners often integrate new knowledge into existing frameworks without fully restructuring their understanding (Lombardi et al., 2016). Thus, while prompt-based learning promotes conceptual development, it may require sustained and repeated engagement to achieve deeper restructuring.

Third, the findings provide insight into the specific features of prompt-based learning that contribute to conceptual understanding. Both quantitative and qualitative results indicate that explanation, reflective, and prediction–evaluation prompts play complementary roles in supporting conceptual change.

Explanation prompts were particularly effective in encouraging participants to externalize their reasoning, making implicit assumptions visible. This aligns with previous research suggesting that explanation-based activities enhance conceptual understanding by requiring learners to articulate causal relationships (Chi, 2015). Reflective prompts, on the other hand, supported metacognitive processes, enabling participants to evaluate, and revise their prior ideas. This reflective engagement is essential for recognizing inconsistencies and initiating conceptual restructuring (Widyasari & Haryanto, 2022).

Prediction–evaluation prompts contributed by creating cognitive conflict, a critical condition for conceptual change. When participants' predictions did not align with experimental outcomes, they were prompted to reconsider their assumptions and adopt alternative explanations. This mechanism is consistent with conceptual change models that emphasize the role of dissonance in triggering knowledge revision (Sinatra et al., 2020).

Despite these positive effects, the study also identified constraints in the effectiveness of prompt-based learning. Some participants engaged with prompts at a superficial level, treating them as procedural tasks rather than opportunities for reflection. In such cases, prompts did not lead to meaningful conceptual change. This finding highlights that the effectiveness of prompts depends not only on their design but also the quality of learner engagement and instructional support.

Overall, this study extends previous research in quantum physics education by demonstrating that prompt-based learning can function as an effective cognitive and metacognitive scaffold, even in the absence of simulations or laboratory-based interventions. The findings suggest that structured prompts facilitate deeper engagement with abstract concepts by promoting explanation, reflection, and conceptual evaluation.

Based on a teacher education perspective, these results highlight the importance of integrating instructional strategies that explicitly target reasoning processes and epistemic understanding, rather than focusing solely on content knowledge. By supporting preservice teachers in developing model-based reasoning, prompt-based learning may contribute to improving the quality of future physics instruction and reducing the persistence of misconceptions in classrooms.

CONCLUSION

The particular study concludes that preservice science teachers initially demonstrate limited and predominantly classical or hybrid conceptualizations of wave–particle duality, indicating a lack of epistemic understanding of quantum models. The findings show that prompt-based learning effectively supports the development of more scientifically aligned conceptual understanding, as evidenced by a significant increase in quantum-consistent reasoning and a shift from ontological interpretations toward epistemic, model-based explanations.

The results further suggest that specific features of prompt-based learning—particularly explanation, reflective, and prediction–evaluation prompts—play a critical role in facilitating conceptual change. These prompts serve as cognitive and metacognitive scaffolds, encouraging learners to externalize their reasoning, evaluate prior conceptions, and resolve inconsistencies through reflective processes. However, the persistence of hybrid reasoning among some participants indicates that conceptual change in quantum physics is gradual and requires sustained engagement.

Based on these findings, it is recommended that future research investigate the long-term stability of conceptual change facilitated by prompt-based learning, and its integration with other instructional approaches, such as simulations and model-based inquiry. Further studies involving larger and more diverse samples, as well as the use of multimodal data (e.g., interviews or think-aloud protocols), are

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also needed to provide a deeper understanding of how conceptual change occurs in complex scientific domains.

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