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Research Article

Representation-Based Instruction in Physics Education: Effects of Classical, Quantum, and Metaphysical Framings on Students' Conceptual Understanding, Epistemological Beliefs, and Tolerance of Uncertainty

Fizik Öğretiminde Temsil Temelli Öğretim: Klasik, Kuantum ve Metafiziksel Çerçevelerin Öğrencilerin Kavramsal Anlama, Epistemolojik İnanç ve Belirsizlik Toleransı Üzerindeki Etkileri

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ABSTRACT

This study investigates the effects of representation-based instruction in physics education on students' conceptual understanding, epistemological beliefs, and tolerance of uncertainty. A mixed-method quasi-experimental design was employed with 30 undergraduate students randomly assigned to three groups: classical representation (n=10), quantum representation (n=10), and metaphysical representation (n=10). All groups studied the same core physics content; however, the instructional framing differed across conditions: the classical group emphasized Newtonian determinism and certainty, the quantum group focused on probabilistic reasoning and observer dependence, and the metaphysical group engaged with thought experiments such as Schrödinger's Cat to explore ontological ambiguity. Data were collected using a Conceptual Understanding Test, an Epistemological Beliefs Scale, and a Tolerance for Uncertainty Scale, supported by open-ended questions and focus group interviews. Quantitative data were analyzed using one-way ANOVA and Tukey HSD tests with effect sizes (η^2), while qualitative data were examined through thematic analysis. Results indicated significant differences among groups, with the metaphysical representation condition yielding the highest gains in conceptual understanding (F (2.27) =9.64, $p<.001$, $\eta^2=.42$) and epistemological beliefs (F (2, F (6.71, $p=.004$, $\eta^2=.33$). Overall, the findings suggest that metaphysical representations can support deeper epistemological awareness and enhance students' ability to cope with uncertainty in physics learning.

Keywords: Conceptual understanding, epistemological beliefs, physics education, representation-based instruction, tolerance of uncertainty

ÖZET

Bu çalışma, fizik öğretiminde temsil temelli öğretim yaklaşımlarının öğrencilerin kavramsal anlama düzeyleri, epistemolojik inançları ve belirsizlik toleransları üzerindeki etkisini incelemektedir. Araştırmada karma yöntemli yarı deneysel desen kullanılmış ve 30 lisans öğrencisi rastgele olarak üç gruba atanmıştır: klasik temsil grubu (n=10), kuantum temsil grubu (n=10) ve metafiziksel temsil grubu (n=10). Tüm gruplarda aynı fiziksel içerik ele alınmış; ancak öğretim süreci temsil çerçevesine göre farklılaştırılmıştır. Klasik grupta Newtonyen kesinlik ve determinizm vurgulanırken, kuantum grupta olasılık temelli açıklamalar ve gözlemci bağımlılığı öne çıkarılmış, metafiziksel grupta ise Schrödinger'in Kedisi gibi düşünce deneyleriyle ontolojik belirsizlik tartışmaları yürütülmüştür. Veri toplama sürecinde Kavramsal Anlama Testi, Epistemolojik İnanç Ölçeği ve Belirsizlik Toleransı Ölçeği uygulanmış; ayrıca açık uçlu sorular ve odak grup görüşmeleriyle nitel veriler elde edilmiştir. Nicel veriler tek yönlü ANOVA ve Tukey HSD testleriyle analiz edilmiş, etki büyüklükleri (η^2) hesaplanmıştır. Bulgular, gruplar arasında anlamlı farklılıklar olduğunu ve metafiziksel temsil grubunun kavramsal anlama ($F(2.27) = 9.64$, $p < .001$, $\eta^2 = .42$) ve epistemolojik inanç düzeylerinde ($F(2.27) = 6.71$, $p = .004$, $\eta^2 = .33$) en yüksek gelişimi gösterdiğini ortaya koymuştur. Sonuç olarak temsil temelli öğretimde metafiziksel çerçevelerin, öğrencilerin epistemolojik farkındalığını güçlendirebileceği ve belirsizlikle başa çıkma becerilerini destekleyebileceği değerlendirilmektedir.

Anahtar Kelimler: Belirsizlik toleransı, epistemolojik inanç, fizik eğitimi, kavramsal anlama, temsil temelli öğretim

INTRODUCTION

Representation plays a central role in physics education by shaping how learners interpret scientific concepts, construct meaning, and position scientific knowledge as certain or uncertain. In many instructional contexts, physics content is predominantly presented through classical representations that emphasize deterministic cause–effect relations and observer-independent measurement. However, the conceptual structure of quantum physics challenges these assumptions by introducing probabilistic reasoning, measurement dependence, and ontological ambiguity. In this respect, representational framings in physics instruction may influence not only students' conceptual understanding but also their epistemological beliefs and tolerance of uncertainty.

In quantum mechanics, uncertainty is not merely a result of measurement limitations; rather, indeterminacy is embedded in the nature of physical systems. Heisenberg's uncertainty principle demonstrated that measurement affects outcomes and alters system states, placing the observer effect at the center of debates on scientific reality (Heisenberg, 1927). This view fundamentally challenges Newtonian assumptions of an "external and absolute reality" and has been widely discussed within the interpretive foundations of quantum theory (Bohr, 1958; Jammer, 1974).

Physics education, shaped largely by the classical paradigm, has often emphasized deterministic explanations and stable, observer-independent truths. Such representational patterns may lead students to view science primarily as the discovery of fixed knowledge rather than as a contextual and model-based enterprise (Hofer & Pintrich, 1997; Topçu, 2012). With quantum physics, the epistemological stance shifts toward probabilistic reasoning and interpretation-dependent meaning making. Nevertheless, this transition has been slow to influence curricular structures and classroom practices, which may limit students' engagement with epistemological complexity (Chinn & Malhotra, 2002).

From a pedagogical perspective, classical representations may foster certainty-oriented reasoning, whereas quantum representations require learners to grapple with probability, the measurement problem, and the role of observation. However, these concepts are often taught superficially, which may restrict opportunities for epistemological reflection and deeper conceptual restructuring (Duschl, 2008). In this context, thought experiments can serve as instructional representations that concretize abstract ideas and open space for students to reflect on reality, knowledge, and the observer's role (Elby & Hammer, 2001).

One of the most widely recognized thought experiments in this domain is Schrödinger's Cat (Schrödinger, 1935). Although originally proposed as a critique of quantum theory, it has been adopted in educational contexts as a representational tool that can support epistemological and ontological discussion by making ambiguity more visible and discussable (Harrigan et al., 2007; Styer, 2000). In the present study, Schrödinger's Cat is not treated as the sole focus of investigation but as one illustrative example within the broader metaphysical representational framing. When integrated into instruction, such thought experiments may help learners engage with uncertainty not only as a conceptual feature of quantum mechanics but also as an epistemic challenge that shapes how scientific knowledge is interpreted and justified.

Confronting uncertainty and ambiguity in learning environments may transform not only conceptual understanding but also epistemological beliefs and learning attitudes. Research indicates that epistemological beliefs influence how students approach learning tasks, connect scientific ideas, and interpret evidence (Bendixen & Rule, 2004; Hofer, 2001). Therefore, representations function not only as explanatory tools but also as cognitive practices that shape how learners relate to knowledge and uncertainty (diSessa, 1993).

In this context, the present study addresses the problem that different representational framings in physics instruction may lead to differences in students' conceptual understanding, epistemological beliefs, and tolerance of uncertainty. Therefore, this study aims to comparatively examine the effects of classical, quantum, and metaphysical representational framings on students' conceptual understanding, epistemological beliefs, and tolerance of uncertainty. Accordingly, the study examines how classical, quantum, and metaphysical representational framings shape students' conceptual understanding, epistemological beliefs, and tolerance of uncertainty. The originality of the study lies in (i) comparing three distinct representational framings (classical, quantum, and metaphysical) within a structured instructional intervention and (ii) examining their combined effects on conceptual understanding, epistemological beliefs, and tolerance of uncertainty. Moreover, metaphysical representations and thought experiments are treated as systematic instructional tools rather than merely illustrative examples (Chen, 2022; Kelly, 2021).

THEORETICAL BACKGROUND

2.1. Quantum Uncertainty and Thought Experiments as Metaphysical Representations

Quantum physics introduces a conception of reality that fundamentally differs from classical determinism by emphasizing probability, indeterminacy, and observation-dependent descriptions of physical systems. In this framework, uncertainty is not merely a limitation of measurement instruments; rather, it reflects the intrinsic structure of nature. Heisenberg's uncertainty principle highlights that measurement influences the system and constrains what can be simultaneously known, thereby positioning the observer as an epistemically significant element of physical description (Dirac, 1930; Heisenberg, 1927). As a result, quantum mechanics challenges classical assumptions of an objective and observer-independent reality, raising questions about how knowledge is constructed, interpreted, and justified (Bohr, 1958; Rovelli, 1996; Baggott, 2011).

This conceptual rupture has important implications for learning and teaching physics. Students who have primarily encountered physics through classical representations may develop deterministic expectations, linear causal reasoning, and a tendency to treat scientific knowledge as fixed and certain (Hammer, 1994; Hofer & Pintrich, 1997). However, quantum topics require learners to engage with probabilistic reasoning, ambiguity, and competing interpretations—features that can be cognitively demanding when instruction remains limited to formula-based or superficial explanations (Chinn & Malhotra, 2002; Duschl, 2008). Therefore, the representational tools used in instruction become critical not only for conceptual learning but also for supporting epistemological reflection.

In this context, thought experiments function as metaphysical representations that make abstract quantum ideas more accessible and discussable. By simulating hypothetical scenarios and inviting learners to reason about "what would happen if…," thought experiments provide a structured space for examining the limits of everyday intuition and the assumptions underlying scientific explanations (Elby & Hammer, 2001). One of the most widely known examples is Schrödinger's Cat (Schrödinger, 1935). Although originally proposed as a critique of quantum theory, it has been adopted in educational contexts as a representational tool that can help students confront ontological ambiguity and reflect on the role of observation in defining physical states (Harrigan et al, 2007; Styer, 2000).

From a pedagogical perspective, metaphysical representations such as thought experiments can support students in engaging with uncertainty at both conceptual and epistemological levels. For learners who struggle with abstract physics, these symbolic structures may provide conceptual anchoring as well as opportunities for deeper reflection on knowledge, evidence, and interpretation (diSessa, 1993). In this way, instruction that integrates metaphysical representations may contribute not only to conceptual development but also to shifts in epistemological beliefs and students' tolerance of uncertainty in scientific reasoning (Bendixen & Rule, 2004; Chen, 2022).

In sum, quantum uncertainty highlights the limitations of classical certainty-based representations and underscores the need for instructional framings that allow students to meaningfully engage with ambiguity. Thought experiments, as metaphysical representations, offer a pedagogical pathway for connecting conceptual learning with epistemological awareness, thereby supporting learners in developing more flexible and reflective approaches to knowledge in physics.

2.2. Types of Representation in Physics Education

Representations are fundamental tools in physics education because they shape how scientific ideas are communicated, interpreted, and learned. In instructional contexts, representations function not only as external forms of information (e.g., diagrams, equations, simulations, narratives) but also as cognitive supports that guide how learners organize knowledge and make sense of scientific phenomena. From this perspective, representation can be viewed as a cognitive practice that structures learners' reasoning and their relationship with knowledge (diSessa, 1993). Therefore, the representational framing adopted in instruction may influence both conceptual learning outcomes and broader epistemological orientations.

In physics education, representations can be broadly categorized according to the epistemic assumptions they emphasize. Classical representations typically rely on deterministic reasoning, linear causality, and observer-independent descriptions. These framings often support clarity and coherence for learners, yet they may also reinforce the perception that scientific knowledge is stable, certain, and absolute (Hofer & Pintrich, 1997; Topçu, 2012). In contrast, quantum representations highlight probabilistic explanations, measurement dependence, and the interpretive nature of scientific models, which can encourage students to view knowledge as contextual and subject to revision (Bohr, 1958; Chinn & Malhotra, 2002). In this sense, representation is not a neutral instructional choice but a lens that shapes how students understand what counts as knowing in physics.

In addition to their explanatory function, representations have been widely discussed in the literature as central mechanisms for conceptual change and scientific reasoning in science learning. Research highlights that students' understanding is shaped not only by the availability of representations but also by their ability to translate and coordinate meaning across different representational systems. In particular, representational transformation and coordination are considered essential for developing conceptual understanding in complex scientific domains (Duval, 2006; Waldrip et al., 2006). Accordingly, representational competence involves using multiple representations as epistemic tools for constructing explanations, evaluating evidence, and negotiating uncertainty in learning processes (Kohl & Finkelstein, 2005; Prain & Waldrip, 2006). From this perspective, representational framings can function as pedagogical environments that either stabilize certainty-oriented reasoning or promote epistemic flexibility by encouraging interpretation, comparison, and reflective sense-making (Tytler et al., 2013).

Beyond classical and quantum framings, metaphysical representations provide an additional instructional layer by engaging learners with thought experiments, ontological ambiguity, and philosophical questioning. Such representations do not aim merely to simplify content; rather, they invite learners to reflect on the limits of observation, the nature of reality, and the interpretive structure of scientific explanations. Thought experiments, for example, can function as metaphysical representational tools that make abstract concepts discussable and support epistemological reflection (Elby & Hammer, 2001; Styer, 2000). A well-known example is Schrödinger's Cat (Schrödinger, 1935), which has been used pedagogically to highlight uncertainty and the role of observation in defining physical states (Harrigan et al., 2007).

Importantly, the educational impact of representations extends beyond conceptual understanding. Students' epistemological beliefs influence how they interpret scientific information, connect concepts, and evaluate evidence (Bendixen & Rule, 2004; Hofer, 2001). When students encounter representations that foreground uncertainty, probability, and interpretive ambiguity, they may be prompted to reconsider certainty-based assumptions and develop more flexible epistemic positions. This process may also relate to tolerance of uncertainty, which can shape how learners respond to complex or ambiguous scientific domains such as quantum physics.

Accordingly, examining different representational framings in physics education is critical for understanding how instructional design influences students' conceptual, epistemological, and affective outcomes. In the present study, classical, quantum, and metaphysical representational framings are treated as distinct instructional conditions to explore their comparative effects on students' conceptual understanding, epistemological beliefs, and tolerance of uncertainty.

2.3. Epistemological Beliefs and Tolerance of Uncertainty

Students' learning experiences in physics education are shaped not only by the content itself but also by their epistemological beliefs regarding that content (Hofer & Pintrich, 1997). Epistemological beliefs encompass individuals' conceptions about the nature, source, limits, and verifiability of knowledge. These beliefs profoundly influence how students engage in learning, their capacity for inquiry, and especially their cognitive responses to ambiguous or contradictory situations (Schommer-Aikins, 2004).

In domains such as quantum physics that are ontologically grounded in uncertainty, students need to be equipped not only conceptually but also epistemologically. In this context, tolerance of uncertainty—defined as an individual's emotional and cognitive response to open-ended, ambiguous, and unpredictable situations—becomes a critical factor in educational processes (Budner, 1962; Furnham & Marks, 2013). Individuals with low tolerance for uncertainty may cling to the search for certainty, which can conflict with the open-mindedness and critical thinking that scientific reasoning demands (Kagan, 1972).

Uncertainty, which is often presented as something to be avoided in physics education, can in fact serve as a powerful tool for learning. Especially in the teaching of highly abstract concepts, students must make sense not only of the concepts themselves but also of the epistemic structures they represent (Chinn & Malhotra, 2002). At this point, metaphysical representations and thought experiments can provide epistemic depth by encouraging students to reflect not only on the content but also on its boundaries, assumptions, and philosophical foundations.

METHOD

3.1. Research Design

This study employs a mixed-methods quasi-experimental design to comparatively investigate the impact of different physical representations on students' conceptual learning, tolerance of uncertainty, and epistemological approaches. This design, which allows for the integrated use of both quantitative and qualitative data, aims to analyze the multilayered effects of pedagogical interventions through both measurable outcomes and interpretive insights (Creswell & Plano

Clark, 2018). The study adopts a pretest–posttest nonequivalent groups design supported by qualitative data, enabling group comparisons across instructional conditions. Within this framework, the impact of the intervention was monitored not only in terms of knowledge acquisition but also in terms of the transformation it created in students' epistemic orientations toward scientific knowledge.

The mixed-methods approach is particularly recommended in fields such as physics education, which involve conceptual complexity and diversity in thinking styles, in order to evaluate the impact of instructional representation formats in a multidimensional manner (Johnson & Onwuegbuzie, 2004). Therefore, epistemological beliefs and tolerance of uncertainty are regarded not only as measurable outcomes but also as developmental dimensions that can be influenced through representational framings in physics instruction (Muis, 2004).

3.2. Participants

The participants of the study consisted of 30 undergraduate students enrolled in science education and physics departments at a public university. Participants were selected on a voluntary basis, and informed consent was obtained prior to their participation in the study procedures. The students, who shared similar academic backgrounds and course histories, were allocated into three equal groups (n = 10). Each group was exposed to a different instructional representation framing in physics education as part of the intervention (classical, quantum, and metaphysical).

In forming the study groups, variables such as age, gender, and academic achievement were considered in order to minimize potential group differences and support sample comparability. The participant profile was appropriate for an instructional intervention study of this nature, comprising individuals with sufficient conceptual competence and familiarity with fundamental physics concepts, thereby contributing to the validity of the collected data. All ethical standards were followed during the research process, and participants' confidentiality was strictly maintained. Detailed group distribution is presented in Table 1.

Table 1

Distribution of Participants by Group, Department, and Gender

Group	Number of participants (n)	Department (Science Ed. / Physics)	Gender (Female / Male)
Classical Representation	10	6 / 4	5 / 5
Quantum Representation	10	5 / 5	6 / 4
Metaphysical Representation	10	6 / 4	4 / 6

3.3. Implementation Process

The implementation process was conducted over three weeks through structured sessions in a university setting. Participants attended a total of six sessions, held twice a week, within their assigned groups. All groups covered the same core physics topics during the intervention; however, the instructional framing, representational emphasis, and classroom activities differed across groups in line with the assigned condition (classical, quantum, or metaphysical representation).

The Classical Representation group received instruction through standard physics narratives emphasizing Newtonian mechanics, deterministic reasoning, and certainty-based explanations. The Quantum Representation group engaged with modern physics concepts such as probabilistic reasoning, the observer effect, and the uncertainty principle. The Metaphysical Representation group explored these themes through thought experiments, visualization techniques, and guided philosophical discussions designed to foreground ontological ambiguity and epistemological reflection. To make the instructional differences across conditions explicit, each group was provided with parallel learning tasks aligned with the same core conceptual targets (e.g., causality, measurement, modeling, and explanation), while the representational framing and classroom activities were systematically varied. In the Metaphysical Representation condition, the same physics topics were explored through structured thought experiments (e.g., Schrödinger's Cat as a case-based narrative), visualization supports (e.g., an instructional diagram illustrating superposition and post-observation collapse; see Appendix 6), and guided inquiry prompts designed to foreground epistemological reflection without shifting the focus away from conceptual learning. For instance, during the "measurement and observation" session, students responded to written prompts such as: "What counts as a physical state before observation?", "How does measurement influence what can be claimed as knowledge?", and "Can two mutually exclusive outcomes be meaningfully discussed within the same explanatory model?". Students then summarized their reasoning in short written justifications and small-group discussion notes, which were used to support reflective comparison across representational framings. A session-by-session overview of the intervention structure and the representational differences across groups is provided in Table 2.

Prior to the intervention, all participants completed the pretest measures. Following the six-session implementation, the same instruments were administered as posttests. After the experimental phase, all participants responded to open-ended questions to capture their reflections on the learning process. Subsequently, focus group interviews were conducted with three students from each group to deepen the qualitative data, and emerging themes were strengthened through triangulation.

Table 2

Session-by-Session Overview of The Intervention Across Representation Conditions

Session	Core physics topic (common to all groups)	Classical Representation (Deterministic framing)	Quantum Representation (Probabilistic/observer-dependent framing)	Metaphysical Representation (Thought-experiment/philosophical framing)
1	Nature of physical reality & scientific explanation	Science as objective description; cause–effect and certainty emphasized	Science as model-based explanation; role of probability introduced	Reality and knowledge as interpretive; "what is real?" discussion prompt
2	Measurement and observation	Measurement as neutral reading of pre-existing reality	Measurement affects system; observer effect and uncertainty emphasized	Observation and reality relation discussed through metaphysical questioning
3	Determinism vs indeterminism	Deterministic laws and predictability (Newtonian worldview)	Indeterminism; probability distributions, limits of prediction	"Can reality be multiple?" ontological ambiguity through scenarios
4	Modeling and representation in physics	Single correct model and fixed truths highlighted	Multiple models; contextual validity, interpretations compared	Models as human constructions; meaning-making and philosophical limits
5	Conceptual change and reasoning	Solving standard problems with fixed rules and certainty	Reasoning under uncertainty; interpreting outcomes probabilistically	Thought experiments + visualization to explore conceptual boundaries
6	Integration and reflection	Review through structured problem-solving and summary	Review through uncertainty-based reasoning and discussion	Reflective synthesis: epistemological reflection + uncertainty tolerance

3.4. Data Collection Tools

A multi-layered data collection strategy grounded in both quantitative and qualitative sources was employed in this study. To assess students' conceptual learning, a Conceptual Understanding Test focusing on the physical representations addressed in the study was developed and administered in a pre-test/post-test format. The test consisted of 12 open-ended items structured under three sections—Classical, Quantum, and Metaphysical representations—with four items in each section (see Appendix 1).

To examine students' approaches to the nature of scientific knowledge, an Epistemological Beliefs Scale adapted from the framework developed by Hofer and Pintrich (1997) was utilized. The scale includes four sub-dimensions: certainty of knowledge, source of knowledge, development of knowledge, and structure of knowledge (see Appendix 2).

In order to examine students' ability to cope with uncertainty in relation to different representational framings, a Tolerance for Uncertainty Scale was administered. The scale consists of 12 items organized under three dimensions: emotional responses, cognitive attitudes, and need for control/certainty (see Appendix 3).

To complement the quantitative data, open-ended questions were administered to all participants at the end of the intervention to capture students' reflections on learning, knowledge, observation, and uncertainty (see Appendix 4).

Additionally, semi-structured focus group interviews were conducted with three students from each group to further enrich the qualitative data. The interview protocol included thematic prompts related to representational experiences, conceptual reasoning, epistemological reflections, and affective responses to uncertainty (see Appendix 5).

This multi-layered data collection strategy enabled the simultaneous examination of conceptual, epistemological, and affective dimensions within the scope of the study.

3.5. Validity and Reliability

Validity and reliability were addressed through complementary quantitative and qualitative strategies consistent with the mixed-methods design of the study.

Content validity of the Conceptual Understanding Test was ensured through expert review by two specialists in physics education, and test items were revised in line with their feedback. The quantitative measurement tools demonstrated acceptable internal consistency, with Cronbach's alpha coefficients of .84 for the Epistemological Beliefs Scale and .87 for the Tolerance for Uncertainty Scale. Sub-dimension reliability values ranged between .72 and.81.

Qualitative credibility was strengthened through methodological triangulation by integrating open-ended written responses and focus group interviews. In addition, qualitative data were coded independently by two researchers, and a high level of inter-rater reliability was achieved ($\kappa > .80$).

Given the relatively small sample size, quantitative analyses were interpreted within an exploratory framework and supported through effect size measures and qualitative triangulation, thereby enhancing the trustworthiness of the findings.

3.6. Data Analysis

Qualitative data were analyzed based on students' open-ended responses and focus group interviews. These data were evaluated using the thematic analysis method proposed by Braun and Clarke (2006). Initially, open coding was applied, and similar codes were then grouped to form overarching themes. The coding process was conducted independently by two researchers, and a high inter-rater reliability coefficient ($\kappa > .80$) was achieved. Quantitative and qualitative findings were integrated at the interpretation stage to strengthen triangulation and provide a more comprehensive explanation of the intervention effects. The themes were organized to directly address the three outcome dimensions of the research question: conceptual understanding, epistemological beliefs, and tolerance of uncertainty. Group sizes were small ($n = 10$); therefore, quantitative analyses were treated as exploratory and interpreted primarily via effect sizes and confidence intervals. Accordingly, quantitative results were interpreted cautiously and complemented by qualitative triangulation.

When presenting participant statements, grouping was done according to the type of representation: students in the classical representation group were coded with the letter "C", those in the quantum representation group with "Q", and those in the metaphysical representation group with "M", each followed by a number.

3.7. Ethics Approval

This study was reviewed and approved by the Ethics Committee (Decision Date: 20.08.2025, Decision No: 408, Session No: 11). The proposal titled *"Representation-Based Instruction in Physics Education: Effects of Classical, Quantum, and Metaphysical Framings on Students' Conceptual Understanding, Epistemological Beliefs, and Tolerance of Uncertainty"* was evaluated in accordance with ethical principles, and it was unanimously decided by the committee members that the research complies with ethical standards.

FINDINGS

This section presents the findings regarding the impact of the instructional interventions on students' levels of conceptual understanding, tolerance of uncertainty, and epistemological orientations. The results are structured based on the integrated interpretation of quantitative and qualitative data sources and analyzed comparatively across the three experimental groups. In line with the purpose of the study, quantitative findings are used to identify group-based differences, whereas qualitative findings are used to explain how students interpreted the representations and made sense of uncertainty. First, the changes in conceptual understanding levels are addressed, followed by an examination of students' differing responses to uncertainty. Finally, findings related to epistemological beliefs are discussed in detail.

Quantitative analysis results reveal the distinctive effects of representation-based instruction on student learning, while qualitative data provide insight into how students made sense of these representations and how such representations influenced their cognitive processes. Accordingly, the findings are presented in a stepwise manner to ensure transparency and to directly address the study outcomes across the three representational conditions.

Table 3

Pre-Test and Post-Test Conceptual Understanding Results by Representation Type

Group	n	M Pre-Test	SD Pre-Test	M Post-Test	SD Post-Test	F Value	p Value	η² (Effect Size)
Classical Representation	10	52.0	5.2	58.0	4.9	-	-	-
Quantum Representation	10	50.0	4.8	71.0	5.5	-	-	-
Metaphysical Representation	10	51.0	5.0	75.0	5.1	9.64	< .001	.42

According to Table 3, students' levels of conceptual understanding significantly differed depending on the type of representation used. Prior to the intervention, there was no significant difference among the groups; the Classical Representation Group (M = 52.00, SD = 5.2), the Quantum Representation Group (M = 50.00, SD = 4.8), and the Metaphysical Representation Group (M = 51.00, SD = 5.0) all showed similar initial levels.

Post-intervention data demonstrate that the type of representation created a meaningful differentiation in conceptual learning. The classical group showed an increase of only 6 points in the post-test (M = 58.00, SD = 4.9), which, although statistically significant, suggests a limited pedagogical impact. In contrast, the quantum group showed a 21-point increase (M = 71.00, SD = 5.5), and the metaphysical group exhibited a 24-point increase (M = 75.00, SD = 5.1).

As a result of the one-way analysis of variance (ANOVA), a significant difference was found between the groups ($F(2, 27) = 9.64$, $p < .001$). The effect size was calculated as $\eta^2 = .42$, indicating that the intervention had a strong impact on conceptual understanding. The Tukey HSD post-hoc test revealed that the metaphysical representation group showed significantly higher conceptual development compared to both the classical and quantum representation groups.

These findings indicate that students' understanding of physical concepts is shaped not only at the level of content but also through the ontological framework in which the concepts are represented. In particular, metaphysical forms of representation facilitate students' development of multiple perspectives on concepts and help them integrate different possibilities into their reasoning processes. This suggests that learning is not merely about arriving at the correct answer, but about reconstructing the meaning of the concept itself.

Table 4

Epistemological Beliefs Scale Results by Representation Type

Group	n	Mean Pre-Test	SD Pre-Test	Mean Post-Test	SD Post-Test	F Value	p Value / η^2 (Effect Size)
Classical Representation	10	3.2	0.4	3.3	0.4	-	-
Quantum Representation	10	3.1	0.3	3.8	0.4	-	-
Metaphysical Representation	10	3.2	0.3	4.1	0.3	6.71	.004 / .33

Table 4 presents the changes in students' epistemological belief levels based on the type of representation used in the instruction. Participants' epistemological beliefs were measured using a five-point Likert-type scale covering four sub-dimensions: certainty of knowledge, source of knowledge, development of knowledge, and structure of knowledge. Accordingly, the analyses were conducted by taking into account the pre-test and post-test mean scores and standard deviations for each group.

According to the pre-test results, all three groups had quite similar levels of epistemological beliefs. No significant differences were found between the Classical Representation Group ($M = 3.2$, $SD = 0.4$), the Quantum Representation Group ($M = 3.1$, $SD = 0.3$), and the Metaphysical Representation Group ($M = 3.2$, $SD = 0.3$). This indicates a homogeneous distribution in participants' approaches to scientific knowledge before the intervention.

Post-test results, however, revealed significant differences. In the Classical Representation Group, only a minimal increase was observed in epistemological belief levels ($M = 3.3$, $SD = 0.4$), which was not statistically significant. In contrast, the Quantum Representation Group showed a notable improvement ($M = 3.8$, $SD = 0.4$); students more strongly accepted that knowledge is probabilistic and that the process of observation plays a decisive role in knowledge production. The highest increase was observed in the Metaphysical Representation Group ($M = 4.1$, $SD = 0.3$). Students in this group developed more advanced and flexible epistemic positions, recognizing that knowledge is not fixed, certain, or absolute, but rather open to context, the observer, and interpretation. In the present analysis, the overall epistemological belief score (averaged across the four sub-dimensions) was used for group comparisons.

The one-way analysis of variance (ANOVA) revealed a statistically significant difference in post-test scores ($F(2, 27) = 6.71$, $p = .004$). The significance of this difference indicates that the types of representations used across groups had varying levels of impact on students' epistemological beliefs. The effect size was calculated as $\eta^2 = .33$, which corresponds to a medium-to-large effect according to Cohen's (1988) classification. This finding suggests that the type of representation not only influences pedagogical effectiveness but also shapes students' fundamental belief structures about scientific knowledge.

Post-hoc analyses using the Tukey HSD test revealed statistically significant differences between the Metaphysical Representation Group and both the Classical and Quantum Representation Groups ($p < .05$). In particular, metaphysical representations appeared to foster a shift in students' approach to knowledge—encouraging them to view it not as absolute truth, but as probabilistic and context-dependent.

These findings suggest that students can undergo a transformation not only in their level of knowledge but also in their epistemic approach to that knowledge. They highlight the power of instructional representations to shape epistemological frameworks.

Table 5

Uncertainty Tolerance Results by Type of Representation

Group	n	Mean Pre-Test	SD Pre-Test	Mean Post-Test	SD Post-Test	F Value	p Value	η^2 (Effect Size)
Classical Representation	10	2.9	0.5	3.1	0.6	–	–	–
Quantum Representation	10	2.8	0.6	3.7	0.5	–	–	–
Metaphysical Representation	10	2.8	0.4	4.2	0.4	8.82	<.001	.39

Table 5 reports the effect of the type of representation on students' uncertainty tolerance. Uncertainty tolerance was assessed using a 5-point Likert-type scale that measures individuals' cognitive and affective responses to ambiguous and hard-to-resolve situations on an epistemic, experiential, or conceptual level. In the analyses, the pre-test and post-test means and standard deviations of each group were taken into account.

Pre-test results indicate that the groups had a balanced initial level: the Classical Representation Group ($M = 2.9$, $SD = 0.5$), the Quantum Representation Group ($M = 2.8$, $SD = 0.6$), and the Metaphysical Representation Group ($M = 2.8$, $SD = 0.4$) started the process with similar scores. These data suggest that students' levels of coping with uncertainty were homogeneous prior to the experiment.

According to the post-test results, significant differences emerged among the types of representation. The Classical Group showed only a marginal increase ($M = 3.1$, $SD = 0.6$). The Quantum Group demonstrated a higher level of improvement ($M = 3.7$, $SD = 0.5$); as students worked particularly with concepts such as the variability of observation and the unpredictability of outcomes, they began to perceive uncertainty as less threatening.

The highest increase was observed in the Metaphysical Representation Group ($M = 4.2$, $SD = 0.4$). In this group, students engaged in discussions based on thought experiments like Schrödinger's Cat, and they learned to accept multiple meanings instead of singular realities. They began to conceptualize uncertainty as a space of intellectual openness. Participants stated that such forms of representation made thinking easier despite increasing complexity.

One-way analysis of variance (One-Way ANOVA) revealed a significant difference among the groups ($F(2, 27) = 8.82$, $p < .001$). This result indicates that the forms of representation applied had a significant effect on students' capacity to cope with uncertainty. The effect size was calculated as $\eta^2 = .39$, which corresponds to a large effect according to Cohen's (1988) criteria. This suggests that representations create a transformation not only in conceptual learning but also in students' levels of cognitive flexibility and tolerance.

Post-hoc analyses revealed significant differences between the Metaphysical Representation Group and the other two groups ($p < .01$). A significant difference was also observed between the Quantum Group and the Classical Group ($p < .05$). These findings show that the type of representation determines not only how well a student understands a concept, but also the epistemic and emotional framework through which that understanding is constructed.

Table 6

Thematic Analysis of Open-Ended Written Responses: Extended Themes, Codes, and Participant Statements

Theme	Sub-Theme	Code	f	Participant Statement
Nature of Knowledge	Certainty of Knowledge	Knowledge is not absolute	12	I realized in these lessons that we should not always seek a definite answer. **(C8)**
	Contextuality of Knowledge	Reality depends on observation	9	If outcomes vary depending on observation, then knowledge is not fixed. **(Q5)**
Perception of Uncertainty	Cognitive Tension	Indecision and confusion	7	The idea that the cat is both dead and alive sounded absurd to me, but I still thought about it. **(M2)**
	Developing Adaptation	Getting used to uncertainty	11	At first, I was disturbed by the uncertainty, but then I accepted it as part of the process. **(Q7)**
Thinking Style	Multiple Perspectives	Developing different viewpoints	14	Interpreting the same situation in different ways felt richer to me. **(M1)**
Pedagogical Value of Representation	Facilitating Understanding	Concrete representation of abstract concepts	10	Thanks to the example with the cat, I was able to better understand what quantum means. **(Q2)**
	Attractiveness	Arousing curiosity	6	I normally find physics boring, but this story caught my interest. **(C5)**
Ontological Reflections	Questioning Reality	What exists?	8	Trying to understand whether the cat exists through observation felt philosophical to me. **(M3)**
	Relation between physical knowledge and existence	Is existence constructed through observation?	5	The idea that reality does not exist until it is observed really affected me. **(Q4)**

Note: C = Classical Representation Group; Q = Quantum Representation Group; M = Metaphysical Representation Group.

In Table 6, open-ended student responses were categorized under five main themes through thematic analysis, and the frequency value (f) of each code was indicated. The frequencies reflect not only which cognitive tendencies were most prominent but also the pedagogical impacts of the types of representation. Themes were interpreted based on both content coherence and frequency data.

The highest frequency value (f = 14) was observed in the code "Developing different viewpoints" under the theme "Thinking Style." This finding indicates that the metaphysical and quantum representation groups, in particular, stimulated alternative modes of thinking among students. The following statement by M1 clearly reflects this: "Interpreting the same situation in different ways expanded my thinking and made me more flexible" (M1). This theme reveals that representational tools have the power not only to transmit knowledge but also to transform patterns of thought.

The theme "Nature of Knowledge" also stands out with high frequency values. Codes such as "Knowledge is not absolute" (f = 12) and "Reality depends on observation" (f = 9) indicate that students moved away from a classical understanding of science toward a more contextual and observer-centered conception of knowledge. C8's statement expresses this shift as follows: "I used to think that knowledge was always fixed, but now I realize that it is not" (C8). Such transformations were particularly evident in the quantum group.

In the theme "Perception of Uncertainty," the code "Getting used to uncertainty" (f = 11) shows that students, despite their initial cognitive tension, began to learn how to live with uncertainty over time. Q7's statement emphasizes this transition: "When I encountered uncertainty, I initially felt uncomfortable, but then I learned to live with it" (Q7). In contrast, the code "Indecision and confusion" (f = 7) indicates that the metaphysical representation group, in particular, created cognitive challenges. These codes offer clues about how affective responses can trigger cognitive restructuring.

Under the theme "Pedagogical Value of Representation," the codes "Concrete representation of abstract concepts" (f = 10) and "Arousing curiosity" (f = 6) reveal that metaphorical and thought experiment-based representations enhanced students' engagement in the lesson and improved their conceptual clarity. Q2's statement is particularly noteworthy: "With examples like Schrödinger's cat, I understood the topic much more easily and in a lasting way" (Q2). This demonstrates that the form of representation influences not only content but also the emotional and cognitive engagement of the student.

The final theme, "Ontological Reflections," has lower frequency values compared to the others (f = 8 and f = 5), but is quite rich in content. M3's statement shows that representation can foster not only learning but also philosophical inquiry: "I started to question whether reality depends on observation or exists independently of it" (M3). Such responses indicate that metaphysical representations can even influence students' understanding of existence.

In conclusion, Table 6 combines both the qualitative nature and quantitative weight of the themes, demonstrating that the types of representation created conceptual, epistemological, and ontological effects on students at different levels.

Table 7

Thematic Analysis Based on Focus Group Interviews

Theme	Sub-Theme	Code	f	Participant Statement
Nature of Knowledge	Epistemic Inquiry	Knowledge is not fixed, it can change	5	Seeing that knowledge can change surprised me because I had always assumed it was absolute. **(Q3)**
Experience of Uncertainty	Emotional Impact	Anxiety and curiosity intertwined	6	The cat's situation made me both anxious and thoughtful; it was the first time I felt this way. **(M2)**
Thinking Style	Paradigm Shift	Development of critical thinking	7	This experience showed me that looking at everything from the same framework is no longer enough for me. **(C6)**
Pedagogical Impact	Depth of Meaning	Concepts becoming more internalized	5	After that thought experiment, the concepts stuck with me more—I was just memorizing before. **(Q4)**
Ontological Awareness	Reality-Construction Relationship	Observation shapes existence	4	I think without observation, we can't know if anything really exists; this had an impact on me. **(M3)**

Note: C = Classical Representation Group; Q = Quantum Representation Group; M = Metaphysical Representation Group.

The focus group interviews presented in Table 7 provide a deepening of the themes derived from the open-ended written data and support them through comparative analysis. These interviews reflect the dimensions of student statements that directly touch on emotion, thought, and conceptual transformation; they also play a role in enhancing qualitative reliability within the triangulation process.

The first theme, "Nature of Knowledge," also stands out prominently in the focus group data. The code "Knowledge is not fixed, it can change" (f = 5) reflects the epistemic shifts observed particularly in the quantum group. Q3's statement clearly reveals this rupture: "Seeing that knowledge can change surprised me because I had always assumed it was absolute" (Q3). This statement indicates that the student moved away from a classical understanding of science toward a more contextual and dynamic epistemology. In the interviews, this tendency was supported by other participants as well.

The second theme, "Experience of Uncertainty," has a high frequency (f = 6) and stands out with statements that reflect participants' affective responses. In particular, the mental disruption and emotional turmoil experienced by students in the metaphysical representation group are clustered under this code. M2's statement expresses this powerfully: "The cat's situation made me both anxious and thoughtful; it was the first time I felt this way" (M2). Here, uncertainty emerges not only as a conceptual but also as an emotional domain of learning. The fact that this theme was more prominently represented in the focus group interviews compared to the written responses indicates that the representations revealed their affective impact more directly.

The third theme, "Thinking Style," has the highest frequency (f = 7). Participants stated that representation-based physics education changed their patterns of thinking and encouraged alternative approaches. C6's statement articulates this transformation as follows: "This experience showed me that looking at everything from the same framework is no longer enough for me" (C6). Such transformations were observed across groups, with particularly strong emphasis in the metaphysical and quantum conditions. The high frequency of this code supports the claim that the pedagogical intervention triggered cognitive restructuring.

The fourth theme, "Pedagogical Impact," shows that students formed deeper connections with concepts through representations. The code "Concepts becoming more internalized" (f = 5) was commonly observed in the quantum group. Q4 expressed this as follows: "After that thought experiment, the concepts stuck with me more—I was just memorizing before" (Q4). This demonstrates that processing abstract scientific concepts through metaphors and thought experiments provides cognitive depth.

The final theme, "Ontological Awareness," has a lower frequency (f = 4), but is quite rich in content. The relationship established between observation and reality is a specific mode of inquiry particularly emphasized by the metaphysical group. M3's statement is noteworthy: "I think without observation, we can't know if anything really exists; this had an impact on me" (M3). Such ontological inquiries may be interpreted as early indications of a shift toward a more plural and observer-sensitive understanding of reality.

In conclusion, the data presented in Table 7 not only confirm the open-ended written responses but also reinforce their content depth and emotional weight by highlighting affective and reflective dimensions of learning that emerged more clearly in spoken interaction. Overall, it is clearly demonstrated that physics education based on different forms of representation creates transformation not only in knowledge transmission but also in thinking style, epistemic orientation, and affective experience. Moreover, a strong convergence was observed across quantitative outcomes, open-ended responses, and focus group interviews. To visualize how these data sources complement one another and which themes are reinforced through triple validation, the triangulation process is presented in Figure 1.

Figure 1

Triangulation Process (Created in Python, Matplotlib.)

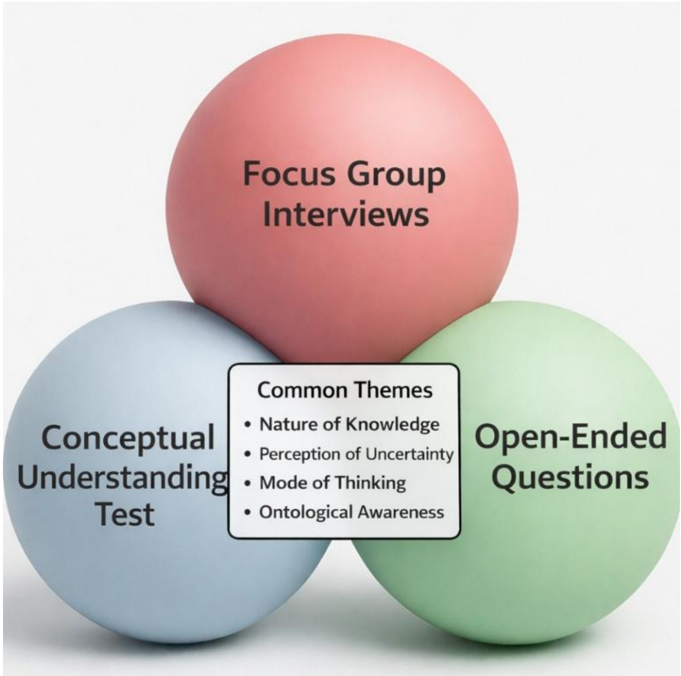

Figure 1 illustrates the thematic convergence across the study's three primary data sources: the conceptual understanding test, open-ended questions, and focus group interviews. Together, these sources complemented one another in terms of methodological pluralism and content depth, enabling a strong triangulation across quantitative and qualitative dimensions.

In the diagram, each circle represents a distinct data source. The conceptual understanding test captured quantitative changes in students' learning outcomes related to core physics concepts (e.g., causality, measurement, and probability-based reasoning). Open-ended questions provided reflective written accounts of how students interpreted scientific knowledge, reality, and the role of observation. Focus group interviews further deepened these insights by revealing affective and epistemological dimensions of students' learning experiences and their engagement with different representational framings.

The central intersection highlights four themes consistently supported across all three sources: Nature of Knowledge, Perception of Uncertainty, Thinking Style, and Ontological Awareness. Collectively, these themes indicate that representational framings shaped not only students' conceptual learning but also their epistemic orientations and responses to ambiguity. For instance, students increasingly described knowledge as contextual and open to interpretation, while uncertainty was framed not only as cognitive tension but also as a productive space for inquiry—particularly in the metaphysical representation condition. Similarly, shifts in thinking style reflected movement from deterministic explanations toward probabilistic and observer-sensitive reasoning, accompanied by emerging ontological reflections on the relationship between observation and reality.

Overall, Figure 1 visually integrates the multilayered effects of representation-based instruction and demonstrates the coherence established across quantitative outcomes, open-ended responses (Table 6), and focus group interviews (Table 7).

Figgure 2

Relational Density Map of Codes (Created in Python using Matplotlib and Seaborn.)

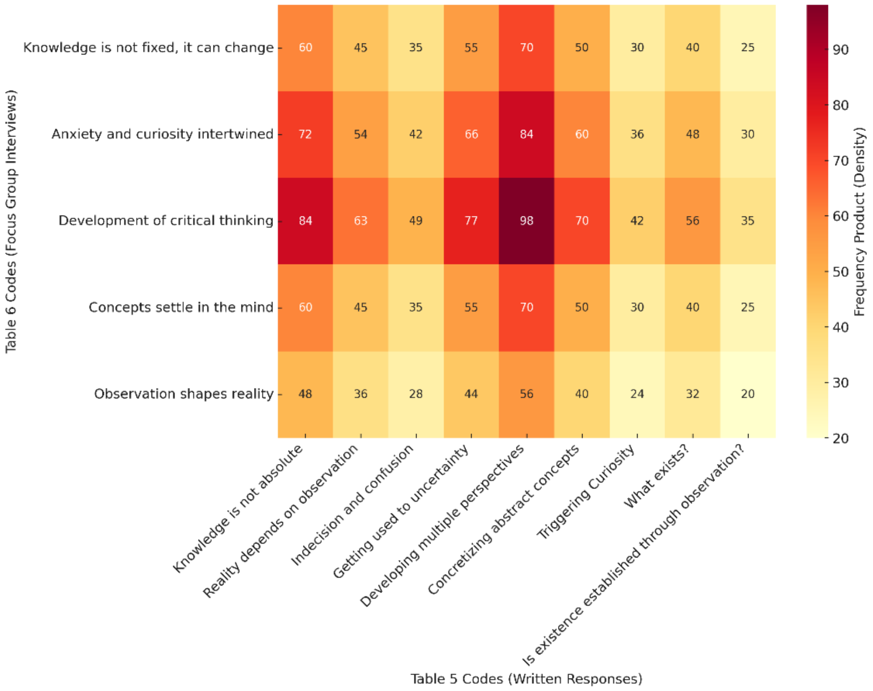

Figure 2 visualizes the relationships between the codes derived from students' open-ended written responses (Table 6) and those expressed during focus group interviews (Table 7) using a frequency-based density map. Rather than representing a statistical correlation, this visualization provides a descriptive indicator of cross-source alignment by highlighting which codes were simultaneously prominent across the two qualitative layers.

Each cell represents a density score computed as the product of the frequency values of the two corresponding codes (written × interview). Higher density values therefore indicate that a given pair of codes was more strongly emphasized across both data sources, suggesting a robust thematic convergence between individual reflections and group-based meaning making.

The highest density values were observed between "Developing multiple perspectives" (written responses) and "Development of critical thinking" (focus groups), indicating that representation-based instruction functioned not only as a means of conveying content but also as a catalyst for cognitive transformation. Similarly, the strong alignment between "Getting used to uncertainty" and "Anxiety and curiosity intertwined" suggests that epistemic uncertainty was experienced not only cognitively but also affectively—particularly under metaphysical representations such as Schrödinger's Cat, which elicited both conceptual expansion and emotional resonance.

Conversely, lower-density pairings do not necessarily imply the absence of a relationship; instead, they may reflect connections that remained implicit, less verbalized, or differently articulated across written and spoken formats. For example, ontologically reflective codes such as "What exists?" showed weaker alignment with more pedagogically structured interview codes, suggesting that philosophical questioning may emerge more readily in individual written responses, whereas focus group interactions may gravitate toward themes that are collectively negotiable and socially shareable.

Overall, Figure 2 goes beyond juxtaposing qualitative codes by illustrating patterns across conceptual, epistemological, and affective dimensions of learning. The map supports the central claim of the study that different representational framings can generate multidimensional transformations in students' learning experiences and meaning-making processes.

DISCUSSION

The main aim of this study was to examine how different representational framings in physics instruction (classical, quantum, and metaphysical) shape transformations in students' conceptual understanding, epistemological beliefs, and tolerance of uncertainty. Findings showed that classical, quantum, and metaphysical representations significantly influenced students' approaches to knowledge and reality, indicating that physics education affects not only content learning but also epistemological and ontological positioning. In this respect, representational choices can be interpreted not merely as instructional techniques, but as epistemic frameworks that shape how learners construct meaning in physics.

Regarding conceptual understanding, the classical group tended to produce closed-ended answers grounded in Newtonian causality, whereas the quantum group developed more flexible responses through probabilistic reasoning and engagement with measurement-related interpretations. The metaphysical group, in turn, demonstrated stronger inquiry-oriented reasoning and meaning-making processes, supported by reflective classroom activities and thought-experiment-based discussions. These findings align with Hammer (1994) and diSessa (1993), who argue that intuitive epistemologies shape conceptual change and reasoning patterns. Notably, the metaphysical representation appeared to influence learning not only at a cognitive level but also at an affective and reflective level, encouraging students to move beyond formula-based reasoning and engage in interpretive sense-making.

In terms of epistemological beliefs, the classical group largely retained more absolutist orientations, whereas the quantum and metaphysical groups demonstrated more flexible and context-dependent epistemic positions. This pattern supports Hofer and Pintrich's (1997) model of epistemological beliefs**.** The metaphysical group, in particular, explicitly questioned the role of observation, interpretation, and model-dependence in knowledge construction, suggesting a shift toward more advanced epistemic positioning (Bendixen & Rule, 2004).

With respect to tolerance of uncertainty, the metaphysical group reported lower levels of stress and demonstrated a greater tendency to treat uncertainty as a productive space for intellectual engagement. This finding is consistent with Bardi et al. (2009), who highlight the relationship between tolerance of ambiguity, creativity, and openness. In this context, uncertainty functioned as a resource for inquiry and meaning-making rather than as a cognitive threat**,** suggesting that an exclusive emphasis on certainty may limit learners' cognitive flexibility and epistemic engagement (Chinn & Malhotra, 2002).

The qualitative themes—nature of knowledge, perception of uncertainty, thinking style, and ontological awareness—further clarified these results. Ontological awareness, in particular, indicated that metaphysical representations created opportunities for students to discuss observation, reality, and interpretive limits in physics, thereby strengthening epistemological reflection. The emergence of ontological awareness suggests that metaphysical representations may support learning outcomes that extend beyond traditional conceptual gains**,** aligning with Kelly (2021) and Duschl (2008), who emphasize the importance of cultivating students' awareness of scientific reasoning and the nature of knowledge.

Triangulation of quantitative results, open-ended responses, and focus group interviews revealed that representational framings impact not only conceptual outcomes but also epistemological and affective dimensions of learning. This convergence across multiple data sources strengthens the interpretive validity of the findings and highlights the multidimensional impact of representation-based instruction (Elby & Hammer, 2001).

Overall, the systematic use of metaphysical representational framings and thought experiments (e.g., Schrödinger's Cat) can foster higher-order outcomes such as epistemological plurality, cognitive flexibility, and productive engagement with uncertainty. However, such approaches should be introduced carefully, as they may also trigger discomfort or skepticism in some learners (Chen, 2022). When appropriately scaffolded, metaphysical representations appear to offer a powerful pedagogical means of making uncertainty both discussable and intellectually meaningful within physics learning environments.

In conclusion, the study demonstrates that representation-based physics instruction shapes not only knowledge acquisition but also students' approaches to scientific reasoning, perceptions of reality, and ways of coping with uncertainty. Accordingly, metaphysical representations can be viewed as pedagogical tools that expand students' epistemic awareness by making uncertainty discussable and intellectually meaningful within physics learning environments.

RESEARCH LIMITATIONS

This study examined the effects of different forms of representation on students' conceptual understanding, epistemological beliefs, and tolerance for uncertainty, but several limitations should be noted.

First, the sample was restricted to 30 university students from physics and science education departments at a single public university, limiting generalizability to other age groups, disciplines, or socio-cultural contexts.

Second, the intervention lasted only three weeks with six sessions, allowing observation of initial shifts but not long-term effects.

Third, data collection relied on a Conceptual Understanding Test, an Epistemological Beliefs Scale, and a Tolerance for Uncertainty Scale. While multidimensional, these tools did not control variables such as cognitive style, prior knowledge, or interest in science.

Fourth, qualitative data from open-ended questions and focus groups reflected subjective perceptions and may have been influenced by researcher interpretation.

Finally, positive outcomes in the metaphysical group may have been shaped by prior dispositions, curiosity, or emotional engagement. These contextual factors were not examined independently, requiring further research on broader pedagogical and psychological dimensions.

CONCLUSION and RECOMMENDATIONS

This study demonstrated that representation-based instruction in physics can function not only as a means of explaining content but also as a pedagogical mechanism that shapes students' ways of thinking, epistemological orientations, and assumptions about scientific reality. In particular, instructional framings grounded in classical, quantum, and metaphysical representations influenced students' conceptual understanding as well as their beliefs about knowledge, observation, and reality. These findings underscore the idea that representations operate as epistemic lenses through which learners interpret both physical phenomena and the nature of scientific knowledge itself.

Students exposed to classical representations tended to retain more absolute and observer-independent views, whereas those in the quantum and metaphysical groups more readily recognized the contextual and interpretive nature of scientific knowledge. This pattern supports Hammer (1994) and indicates that instructional experiences that foreground probability, interpretation, and uncertainty may invite deeper epistemological reflection (Chinn & Malhotra, 2002; Elby & Hammer, 2001). Accordingly, representational diversity in instruction emerges as a key factor in supporting epistemological development alongside conceptual learning.

Importantly, metaphysical representational framings—often implemented through structured thought experiments (e.g., Schrödinger's Cat) —supported students in engaging with ambiguity and questioning certainty-based assumptions. In this respect, representation becomes not only a tool for visualization but also a mode of reasoning that reshapes learners' relationship with knowledge and uncertainty (diSessa, 1993; Duschl, 2008). By making uncertainty explicit and discussable, metaphysical representations appear to foster intellectual openness and reflective engagement rather than avoidance of complexity.

The findings highlight the need for teachers to reconsider instructional attitudes toward representations. Rather than dismissing metaphysical examples as abstract, science teachers may employ them to enhance cognitive flexibility and support students' ability to cope with uncertainty (Hofer & Pintrich, 1997). Within teacher education, this also calls for integrating epistemological awareness so that teacher candidates can reflect on their own beliefs as well as their students' epistemic development (Bendixen & Rule, 2004; Kelly, 2021). From this perspective, teacher education programs may benefit from explicitly addressing how different representational framings shape learners' epistemic expectations and responses to uncertainty.

For future research, three directions are suggested: (1) examining metaphysical representations across different age groups, particularly their effects on affective variables such as curiosity and engagement (Chen, 2022); (2) exploring the impact of other thought experiments—such as Maxwell's Demon, Boltzmann Brain, or Laplace's Demon—on physics education; and (3) investigating the long-term effects of representation-based instructional models, including whether epistemological transformations persist over time. Additionally, more work is needed on how scientific uncertainty elicits anxiety or curiosity, given its psychological significance (Bardi, Guerra, & Ramdeny, 2009). Future studies may also consider comparative instructional designs that systematically vary representational framings to further clarify their differential cognitive, epistemological, and affective impacts.

In conclusion, metaphysical representations and thought-experiment-based instructional designs should be viewed as more than narrative elements; they constitute representational tools that can expand epistemic awareness and transform learning. Representation is not only the vehicle of knowledge but also a framework through which meaning is constructed, making its pedagogical use both powerful and responsible. Thus, thoughtfully designed representational practices hold significant potential for enriching physics education by supporting students' engagement with complexity, uncertainty, and the interpretive nature of scientific knowledge.

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GENİŞLETİLMİŞ ÖZET

Giriş

Fizik öğretiminde kullanılan temsiller, öğrencilerin bilimsel kavramları nasıl anlamlandırdığını, bilimsel bilginin doğasına ilişkin inançlarını ve belirsizlik karşısındaki tutumlarını doğrudan şekillendiren güçlü pedagojik araçlardır (diSessa, 1993; Duschl, 2008). Geleneksel öğretim pratiklerinde fizik çoğunlukla klasik temsiller üzerinden sunulmakta; bu yaklaşım nedensellik, determinizm ve kesinlik merkezli bir bilim anlayışını desteklemektedir. Ancak modern fiziğin özellikle kuantum mekaniği bağlamında ortaya koyduğu olasılıksallık, ölçüm bağımlılığı ve gözlemci etkisi gibi unsurlar, bilginin mutlak ve değişmez olduğu varsayımını zorlamakta; öğrencilerin epistemolojik düzeyde daha bağlamsal ve yoruma açık bir bilim anlayışı geliştirmesini gerektirmektedir (Bohr, 1958; Jammer, 1974).

Bu çerçevede kuantum fiziği yalnızca yeni kavramlar sunan bir içerik alanı değil; aynı zamanda öğrencilerin "bilgi nedir?", "bilimsel gerçeklik nasıl kurulur?" ve "belirsizlik öğrenme sürecinde nasıl anlamlandırılır?" gibi temel sorularla yüzleşmesini sağlayan bir düşünme zemini oluşturmaktadır (Chinn & Malhotra, 2002; Hofer, 2001). Özellikle düşünce deneyleri, soyut ve karmaşık kuantum kavramlarını pedagojik olarak görünür kılarken, öğrencilerin ontolojik ve epistemolojik sorgulamalar geliştirmesine de alan açabilmektedir (Elby & Hammer, 2001; Styer, 2000). Schrödinger'in Kedisi düşünce deneyi bu tür temsillerin en bilinen örneklerinden biri olmakla birlikte, bu çalışmada tek başına araştırmanın odağı olarak değil, metafiziksel temsil çerçevesi içinde kullanılan temsillerden biri olarak ele alınmıştır (Schrödinger, 1935).

Bu araştırmanın temel problemi, fizik öğretiminde kullanılan farklı temsil çerçevelerinin öğrencilerin yalnızca kavramsal öğrenme düzeylerini değil; aynı zamanda epistemolojik inançlarını ve belirsizliğe toleranslarını da farklı biçimlerde dönüştürme potansiyeline sahip olup olmadığının ortaya konulmasıdır.

Kuramsal Çerçeve

Kuantum mekaniği, klasik fiziğin kesinlik ve determinizm temelli bilgi anlayışına karşılık, olasılıksal ve bağlama duyarlı bir gerçeklik tasavvuru sunmaktadır. Heisenberg'in belirsizlik ilkesi, ölçümün yalnızca pasif bir okuma süreci olmadığını; gözlem sürecinin fiziksel sistemin durumunu etkileyebileceğini vurgulamıştır (Heisenberg, 1927). Bohr'un tamamlayıcılık yaklaşımı ise fiziksel gerçekliğin tek bir temsil üzerinden değil, farklı gözlem koşullarına bağlı olarak farklı biçimlerde anlam kazandığını ileri sürmektedir (Bohr, 1958). Bu durum, fizik öğrenme süreçlerinde "tek doğru" merkezli açıklamalardan ziyade, model temelli ve yorumlayıcı düşünmenin önemini artırmaktadır (Duschl, 2008).

Öğrencilerin epistemolojik inançları, öğrenme süreçlerinde bilgiyi nasıl yapılandırdıklarını ve bilimsel açıklamaları nasıl değerlendirdiklerini belirleyen kritik bir değişkendir (Hofer & Pintrich, 1997; Schommer-Aikins, 2004). Bilgiyi kesin, değişmez ve otoriteye bağlı gören öğrenciler; belirsizlik içeren, olasılıksal ve çoklu yorum gerektiren durumlarda daha fazla bilişsel direnç gösterebilmektedir (Bendixen & Rule, 2004). Buna karşılık bilgiyi gelişen, bağlamsal ve yorumlanabilir bir yapı olarak gören öğrencilerin daha esnek düşünme biçimleri geliştirdiği ve öğrenme sürecinde daha üretken stratejiler benimsediği vurgulanmaktadır (Hofer, 2001).

Belirsizliğe tolerans ise bireylerin karmaşık, çelişkili ve kesin çözüme kolayca ulaşmayan durumlarla başa çıkabilme kapasitesini ifade etmektedir (Budner, 1962). Bu kavramın öğrenme bağlamındaki önemi, özellikle belirsizlik ve yorum çeşitliliği içeren alanlarda daha belirgin hâle gelmektedir (Furnham & Marks, 2013). Kuantum fiziği gibi belirsizlikle örülü içeriklerde öğrencilerin belirsizliği yalnızca "hata" ya da "eksiklik" olarak değil, bilimsel düşünmenin doğasına ait bir boyut olarak anlamlandırabilmesi hem kavramsal öğrenmeyi hem de epistemolojik gelişimi destekleyebilmektedir (Chinn & Malhotra, 2002).

Amaç

Bu çalışmanın amacı, fizik öğretiminde kullanılan üç farklı temsil çerçevesinin—klasik, kuantum ve metafiziksel—öğrencilerin (i) kavramsal anlama düzeyleri, (ii) epistemolojik inançları ve (iii) belirsizliğe toleransları üzerindeki etkilerini karşılaştırmalı olarak incelemektir. Çalışmanın özgün yönü, metafiziksel temsillerin (düşünce deneyleri, görselleştirme teknikleri ve yönlendirilmiş tartışmalar gibi) sistematik bir öğretim yaklaşımı olarak yapılandırılması ve bu yaklaşımın bilişsel çıktılarla birlikte epistemolojik ve afektif boyutlar açısından da değerlendirilmesidir (Elby & Hammer, 2001; Kelly, 2021).

Yöntem

Araştırmada karma yöntemli deneysel desen benimsenmiştir. Çalışma grubunu fen bilgisi öğretmenliği ve fizik bölümlerinde öğrenim gören 30 lisans öğrencisi oluşturmaktadır. Katılımcılar rastgele biçimde üç gruba atanmıştır: klasik temsil grubu (n=10), kuantum temsil grubu (n=10) ve metafiziksel temsil grubu (n=10). Uygulama süreci üç hafta boyunca toplam altı oturum şeklinde yürütülmüştür.

Tüm gruplarda aynı temel fizik konu başlıkları ele alınmış; ancak öğretim süreci temsil çerçevesi açısından farklılaştırılmıştır. Klasik temsil grubunda Newtoncu mekanik, kesinlik ve nedensellik vurgusu ön planda tutulmuştur. Kuantum temsil grubunda olasılıksal akıl yürütme, gözlemci etkisi ve belirsizlik ilkesi gibi modern fizik temaları merkeze alınmıştır. Metafiziksel temsil grubunda ise düşünce deneyleri (ör. Schrödinger'in Kedisi), görselleştirme teknikleri ve yönlendirilmiş felsefi tartışmalar aracılığıyla ontolojik belirsizlik ve epistemolojik sorgulama desteklenmiştir (Schrödinger, 1935; Styer, 2000).

Nicel veriler ANOVA ve Tukey HSD testleriyle analiz edilmiş, etki büyüklükleri (η^2) hesaplanmıştır. Grup büyüklüklerinin sınırlı olması nedeniyle nicel bulgular doğrulayıcı bir çerçeveden ziyade keşfedici (exploratory) düzeyde ele alınmış; sonuçların yorumlanmasında etki büyüklükleri ve nitel verilerle sağlanan üçgenleme temel alınmıştır.

Bulgular

Bulgular, temsil temelli öğretimin öğrencilerin kavramsal anlama, epistemolojik inanç ve belirsizliğe tolerans düzeylerinde farklılaşan etkiler oluşturduğunu göstermektedir. Nicel sonuçlara göre kavramsal anlama açısından klasik grup sınırlı bir artış gösterirken (M=58), kuantum (M=71) ve metafiziksel (M=75) gruplarda daha belirgin kazanımlar ortaya çıkmıştır. Gruplar arası farkın anlamlı olduğu görülmüş (F=9.64, $p<.001$) ve etki büyüklüğü yüksek düzeyde raporlanmıştır (η^2=.42). Epistemolojik inançlar açısından ön test puanları gruplar arasında birbirine yakın bulunmuş (Klasik: M=3.2, SD=0.4; Kuantum: M=3.1, SD=0.3; Metafiziksel: M=3.2, SD=0.3) ve bu durum uygulama öncesinde grupların homojen bir başlangıç düzeyine sahip olduğunu göstermiştir. Son test sonuçları ise klasik grupta çok sınırlı bir artışa işaret ederken (M=3.3, SD=0.4), kuantum (M=3.8, SD=0.4) ve özellikle metafiziksel grupta (M=4.1, SD=0.3) belirgin bir yükselme olduğunu ortaya koymuştur. Son test puanları üzerinden yapılan tek yönlü ANOVA analizi gruplar arasında anlamlı farklılık bulunduğunu göstermiştir (F (2, F (6.71, p=.004) ve etki büyüklüğü orta-yüksek düzeyde hesaplanmıştır (η^2=.33). Belirsizliğe tolerans bulgularında da benzer bir örüntü gözlenmiştir. Ön testte gruplar birbirine yakın düzeydedir (Klasik: M=2.9, SD=0.5; Kuantum: M=2.8, SD=0.6; Metafiziksel: M=2.8, SD=0.4). Son testte klasik grup sınırlı bir artış göstermiş (M=3.1, SD=0.6), kuantum grup daha yüksek düzeyde gelişim sergilemiş (M=3.7, SD=0.5), metafiziksel grup ise en yüksek düzeye ulaşmıştır (M=4.2, SD=0.4). ANOVA sonuçları gruplar arasında anlamlı fark bulunduğunu ortaya koymuş ($F(2,27) = 8.82$, $p < .001$) ve etki büyüklüğü yüksek düzeyde bulunmuştur ($\eta^2 = .39$). Nitel bulgular, nicel sonuçları derinleştirerek özellikle kuantum ve metafiziksel temsillerin öğrencilerde bilginin mutlak olmadığı, gözleme ve bağlama göre değişebileceği yönünde epistemik farkındalık geliştirdiğini göstermiştir. Açık uçlu yanıtlar ve odak grup görüşmelerinde "bilginin mutlak olmadığı" (f=12), "gerçekliğin gözleme bağlı olduğu" (f=9) ve "belirsizliğe zamanla alışma" (f=11) kodlarının öne çıktığı; öğrencilerin belirsizliği yalnızca kaygı değil, aynı zamanda merak ve düşünsel açılım yaratan bir deneyim olarak ifade ettikleri belirlenmiştir. Grup büyüklüklerinin sınırlı olması (n=10) nedeniyle nicel bulgular keşfedici düzeyde değerlendirilmiş; sonuçların yorumlanmasında etki büyüklükleri ve nitel verilerle sağlanan üçgenleme temel alınmıştır.

Tartışma

Bulgular, fizik öğretiminde kullanılan temsil çerçevelerinin yalnızca kavramsal öğrenmeyi değil, öğrencilerin bilginin doğasına ilişkin inançlarını ve belirsizlikle kurdukları ilişkiyi de dönüştürebildiğini göstermektedir. Klasik temsil yaklaşımı, kesinlik ve tek doğru merkezli düşünmeyi destekleyerek epistemik esnekliği sınırlı düzeyde bırakmıştır. Buna karşılık kuantum ve özellikle metafiziksel temsiller, öğrencilerin bilginin bağlamsal doğasını fark etmesine, belirsizliği daha üretken biçimde anlamlandırmasına ve farklı yorum olasılıklarını düşünmesine katkı sağlamıştır (Hofer, 2001; Chinn & Malhotra, 2002).

Metafiziksel temsillerin güçlü etkisi, düşünce deneyleri ve tartışma temelli yapıların öğrencilerde hem bilişsel esneklik hem de ontolojik sorgulama alanı açmasıyla açıklanabilir (Elby & Hammer, 2001; Styer, 2000). Bununla birlikte, bazı öğrencilerde belirsizlik temelli tartışmaların başlangıçta kafa karışıklığı ve kaygı yarattığı da görülmüştür. Bu nedenle metafiziksel temsillerin öğretim sürecine dengeli biçimde entegre edilmesi ve pedagojik rehberlikle desteklenmesi önemlidir (Duschl, 2008).

Sonuç ve Öneriler

Bu çalışma, fizik eğitiminde kullanılan temsil biçimlerinin öğrencilerin yalnızca kavramsal kazanımlarını değil, epistemolojik yönelimlerini ve belirsizliğe toleranslarını da etkileyebildiğini ortaya koymuştur. Kuantum ve metafiziksel temsiller, öğrencilerin belirsizliği bilimsel düşünmenin doğal bir parçası olarak görmesine, bilgiyi daha bağlamsal ve yoruma açık biçimde değerlendirmesine ve çoklu bakış açıları geliştirmesine katkı sağlamıştır (Bendixen & Rule, 2004; Hofer & Pintrich, 1997)

Öğretmen yetiştirme programlarında farklı temsil çerçevelerine dayalı öğretim tasarımlarına daha fazla yer verilmesi; epistemolojik farkındalığı, bilişsel esnekliği ve belirsizlikle başa çıkma becerisini destekleyebilir. Gelecek araştırmalarda daha geniş örneklemler, daha uzun süreli uygulamalar ve farklı düşünce deneyleriyle benzer karşılaştırmalar yapılması; ayrıca belirsizliğin duygusal boyutlarının daha ayrıntılı incelenmesi önerilmektedir (Furnham & Marks, 2013).

APPENDICES

APPENDIX 1 – CONCEPTUAL UNDERSTANDING TEST

Please read each question carefully and respond in an open-ended manner based on the given physics representation. Your answers should include conceptual explanations and justifications.

A. Classical Physics Representation (Newtonian Approach)

1. Explain the motion of an object accelerating under a constant force. Which physical quantities change in this situation?

2. Within the framework of Newton's Third Law, how would you explain a ball bouncing back after hitting a wall?

3. When air resistance is neglected, why do two objects with different masses reach the ground at the same time when dropped from rest?

4. What does the concept of a "deterministic universe" mean in classical mechanics? Explain this idea with an example.

B. Quantum Physics Representation

5. Explain the double-slit experiment in which an electron passes through two slits simultaneously. Why does this situation contradict the classical understanding of physics?

6. Explain the concept of quantum superposition with an example. Discuss how this concept is related to measurement.

7. What is the effect of the observer on quantum systems? How does this differ from the classical view of observation?

8. How does the concept of probability operate in quantum mechanics? What epistemological questions does this raise regarding the certainty of knowledge?

C. Metaphysical Representation (Schrödinger's Cat and Thought Experiments)

9. Explain what function a thought experiment may serve in physics education. How can such representations influence students' conceptual thinking?

10. Discuss the relationship between physical reality and representation through the question: "Does a system have a definite state before it is observed?"

11. From both physical and epistemological perspectives, evaluate the question: "Why may it not always be possible to obtain certain knowledge before measurement?"

12. How can a thought experiment such as Schrödinger's Cat be used in an instructional setting? Evaluate the conceptual and epistemological effects that such a representation may create in students.

APPENDIX 2 – EPISTEMOLOGICAL BELIEFS SCALE

Source: Adapted based on Hofer & Pintrich (1997).

Please read each statement carefully and select the option that best reflects your opinion. There are no right or wrong answers.

Rating Scale:
1 = Strongly Disagree 2 = Disagree 3 = Neutral 4 = Agree 5 = Strongly Agree

A. Source of Knowledge

(Measures students' beliefs about whether knowledge is external (from authority) or internal (constructed by the learner).)

1. Teachers provide correct information about everything they say.

2. Information written in books should generally be accepted without questioning.

3. New knowledge can only be learned from authority figures.

4. Expert opinions are sufficient to understand knowledge.

B. Certainty of Knowledge

(Measures beliefs about whether knowledge is fixed/absolute or changes depending on context.)

5. There is only one correct knowledge, and it does not change over time.
6. A question can have only one correct answer.
7. Scientific facts never change.
8. Knowledge is either completely true or completely false.

C. Structure of Knowledge (Simplicity–Complexity)

(Measures beliefs about whether knowledge consists of simple facts or complex interrelated concepts.)

9. Knowledge consists only of simple facts that must be memorized.
10. Understanding the relationships between concepts is not as important as learning them.
11. Knowledge consists of independent and separate pieces.
12. Things to be learned are generally direct and clear.

D. Control of Learning and Ability

(Measures beliefs about whether learning is under one's control or depends on innate ability.)

13. If I cannot understand something immediately, I will never be able to learn it.
14. Some people are born intelligent, so learning is easier for them.
15. Because my intelligence is limited, it is not possible for me to learn some topics.
16. Not everyone can learn at the same level because ability is innate.

APPENDIX 3 – TOLERANCE OF UNCERTAINTY SCALE

Source: Adapted based on Budner (1962) and Furnham & Marks (2013).

The following statements will help us understand how you feel and think when you encounter uncertain situations. Please read each item carefully and select the option that best fits you.

Rating Scale:
1 = Strongly Disagree 2 = Disagree 3 = Neutral 4 = Agree 5 = Strongly Agree

A. Emotional Responses to Uncertainty

1. I feel uneasy in uncertain situations.
2. Making decisions with uncertain information makes me uncomfortable.
3. My anxiety increases when I do not know what will happen.
4. Open-ended questions make me feel stressed.

B. Cognitive Attitudes Toward Uncertainty

5. Uncertain situations help me think creatively.

6. Thinking about multiple possibilities rather than certainty interests me.

7. I enjoy thinking about unclear topics.

8. Uncertainty in science is necessary for progress.

C. Need for Control and Search for Certainty

9. When learning, I want everything to be clear and definite.

10. Concepts such as uncertainty in physics seem confusing to me.

11. Unexplainable things make me uncomfortable.

12. I believe that every question must have one correct answer.

APPENDIX 4 – OPEN-ENDED QUESTION FORM

This form was developed to evaluate participants' intellectual approaches and conceptual orientations.

Please read the following questions carefully and express your thoughts clearly and in detail. For each question, you are expected to reflect on your own learning experience and conceptual approach. There are no right or wrong answers; what matters is your personal interpretation.

1. How did you evaluate the representational framing you encountered during the learning process (classical, quantum, or metaphysical)? What did this representation contribute to your conceptual understanding?

2. At which points did you experience uncertainty while learning physical concepts? How did these uncertainties affect your way of thinking?

3. Do you think there is a certain and fixed way of reaching knowledge? Why or why not?

4. In your opinion, how does the role of the observer influence scientific knowledge? What do you think about this issue particularly in the context of quantum and metaphysical representations?

5. What did the Schrödinger's Cat thought experiment mean to you? Explain how this representation influenced your perception of reality.

6. In your view, is uncertainty an obstacle to scientific thinking, or an opportunity for scientific progress? Explain based on your own experience.

7. How did the representational framings change your conceptual understanding and your approach to the nature of knowledge? Explain this change with an example.

APPENDIX 5 – FOCUS GROUP INTERVIEW GUIDE

This semi-structured focus group interview guide was developed to explore students' experiences, conceptual approaches, and emotional responses based on the type of representation used during instruction.

Participant Groups:

- Classical Representation Group (C)
- Quantum Representation Group (Q)
- Metaphysical Representation Group (M)

Number of Participants: Three students from each group

1. Perceptions of the Representation

- How would you describe the representational framing used during the instructional process?
- Was this representation clear and understandable for you, or did you find it complex? Why?

2. Conceptual Approach

- How did the representational framing influence your understanding of physical concepts?
- Was there any concept that you particularly struggled with or had an "aha moment" about? Could you explain?
- Did the representational framing help you establish relationships between concepts? If so, how?

3. Epistemological Response

- What did this instructional experience make you think about the structure and nature of knowledge?
- Did elements such as the observer effect, probability, or measurement change your understanding of knowledge?
- How did it affect you to consider that knowledge may not be fixed?

4. Coping With Uncertainty

- Did the representational framing encourage you to confront uncertainty?
- Did this experience make you feel discomfort, or did it arouse curiosity?
- How did you cope with uncertainty during the learning process?

5. Emotional and Affective Responses

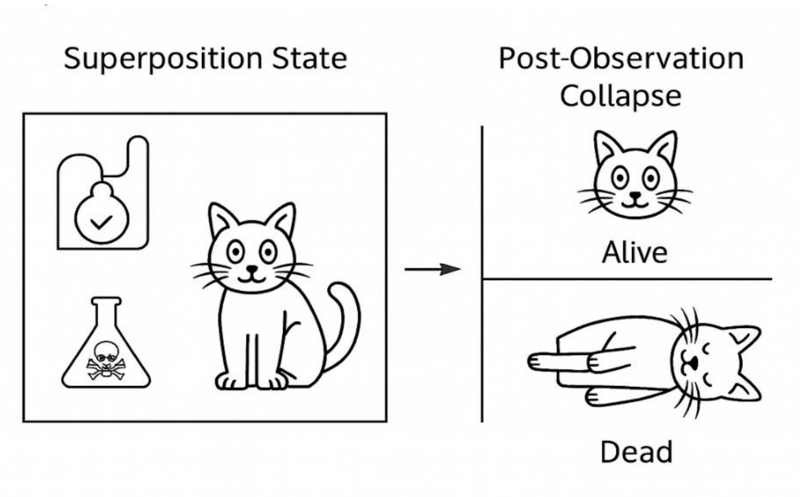
- What was the most emotionally impactful moment for you during the instructional process?
- Did the representational framing lead to emotional responses such as motivation, anxiety, or interest?
- Do you think the representational framing had an emotional influence on your way of thinking? Why or why not?

6. Overall Evaluation

- How would you evaluate this experience overall?
- What was the most memorable part for you?

• If you were to compare the representational framings with one another, what would you say?

APPENDIX 6 – A SCHEMATIC REPRESENTATION OF SCHRÖDINGER'S CAT THOUGHT EXPERIMENT



Note. This visual representation was used as an instructional support tool to facilitate discussion in the metaphysical representation condition (created using Canva).