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An Integrated Diagnostic Profile of Undergraduate Students' Cognitive Processes, Mental Models, and Learning Interest in Moon Phase Concepts Using Rasch Measurement and Qualitative Analysis

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Abstract: This study profiled undergraduate students' cognitive processes, mental models, and learning interest regarding moon phases using an integrated empirical approach. A convergent mixed-methods design was employed in which quantitative and qualitative data were collected concurrently and then merged. Cognitive processes were measured using an eight-item test aligned with the revised Bloom's taxonomy (C3–C5), and learning interest was assessed using a Likert scale questionnaire; mental models were inferred from students' written explanations and confirmed through semi-structured interviews. A total of 65 first-year students from Universitas Pendidikan Indonesia participated through purposive sampling. Quantitative data were analyzed using descriptive statistics and the Rasch model, whereas qualitative data were analyzed thematically. The Rasch analysis indicated acceptable item fit (MNSQ 0.65–1.27), high item reliability (0.96), and acceptable person reliability (0.73), although the two most difficult items (CE1 and T) exceeded most students' ability level. Mean performance decreased systematically across cognitive levels, from applying (C3) to analyzing (C4) and evaluating (C5). Mental-model analysis showed that 40.0% of students held Initial models, 50.8% Synthetic models, and 9.2% Scientific models, while 61.5% reported high learning interest. These results reveal a consistent gap between students' motivational readiness and their cognitive–conceptual readiness, indicating that high interest functions as an entry condition for engagement rather than an indicator of conceptual mastery. These findings indicate that students' high learning interest should be treated as motivational readiness rather than evidence of conceptual mastery, thereby highlighting the need for scaffolded, diagnostic-based, and differentiated astronomy instruction.

Keywords: cognitive processes, learning interest, mental models, moon phases, rasch analysis.

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INTRODUCTION

Moon phases are among the fundamental topics in introductory astronomy and physics education because they require learners to connect an observable celestial phenomenon with the relative positions and motions of the Sun, Earth, and Moon. Although moon phases can be observed in everyday life, understanding the underlying mechanism is cognitively demanding: learners must integrate the concepts of illumination, lunar revolution, observer perspective, and three-dimensional spatial reasoning to explain the periodic change in the Moon's visible shape (Lelliott & Rollnick, 2010; Plummer, 2014;

Ubben et al., 2022). This complexity makes moon phases an appropriate context for examining learners' cognitive processes, because understanding requires not only factual recall but also higher-order thinking, such as applying, analyzing, and evaluating scientific explanations (Anderson & Krathwohl, 2001; Sari et al., 2019).

Empirical studies in astronomy education consistently report persistent difficulties with moon phase phenomena. Many learners can recall the sequence of lunar phases but struggle to explain the causal relationship between sunlight, the relative positions of celestial bodies, and the observer's viewpoint on Earth (Bayraktar, 2009; Kurnaz & Deðermenci, 2012; Syuhendri et al., 2022). Misconceptions remain prevalent, including the beliefs that moon phases are caused by Earth's shadow, atmospheric obstruction, or intrinsic changes in lunar brightness (Bryce & Blown, 2013; Lelliott & Rollnick, 2010; Syuhendri et al., 2022). Such misconceptions indicate that learners' conceptual structures are often fragmented and not yet aligned with scientific explanations. At the undergraduate level, the issue becomes more critical, since learners are expected to move beyond recognition toward deeper scientific reasoning involving application, analysis, and evaluation (Bayraktar, 2009; Kaharu & Mansyur, 2021; Ubben & Bitzenbauer, 2022)

Cognitive processes play a central role in physics learning because they describe how learners use knowledge to construct explanations and solve problems. The revised Bloom's taxonomy provides a structured framework for analyzing cognitive levels, particularly applying (C3), analyzing (C4), and evaluating (C5)(Anderson & Krathwohl, 2001). In the context of moon phases, applying involves identifying or explaining lunar phases using known concepts; analyzing involves interpreting the spatial relationships among the Sun, Earth, and Moon; and evaluating involves judging the correctness of explanations or comparing alternative representations. Differences in performance across these levels suggest that learners may succeed in basic application tasks yet still encounter difficulty with spatial reasoning and conceptual evaluation (Lindsey et al., 2024; Tomlinson et al., 2017; Treagust, 2008).

In addition to cognitive processes, mental models are crucial in shaping learners' understanding of scientific phenomena. A mental model is an internal cognitive representation used to explain, predict, and reason about a phenomenon (Greca & Moreira, 2000; Lindsey et al., 2024). Mental models in science learning are commonly categorized as Initial, Synthetic, and Scientific, depending on their coherence and alignment with scientific knowledge: Initial models are dominated by intuitive or incorrect ideas, Synthetic models combine partial scientific understanding with misconceptions, and Scientific models reflect coherent and accurate conceptual structures (Vosniadou, 2008). In moon phase learning, learners frequently display Synthetic models in which scientific elements, such as sunlight, are partially understood, but causal reasoning remains inaccurate (Bryce & Blown, 2012; Kurnaz & Deðermenci, 2012)

Learning interest represents the affective dimension that directs attention, persistence, and willingness to engage with difficult material (Hidi & Renninger, 2006). Students with strong interest are more likely to seek resources and persist when concepts are challenging. Interest, however, does not guarantee conceptual understanding. A learner may remain enthusiastic while processing information superficially or retaining an incomplete mental model. Interest should therefore be examined alongside cognitive performance and mental model quality to more accurately characterize learning readiness.

Differentiated instruction provides a relevant framework for responding to diverse learner profiles by aligning content, activities, and instructional support with learners' readiness, interests, and learning profiles (Tomlinson et al., 2003, 2017). Designing such instruction, however, presupposes a clear, empirically grounded understanding of who the learners are. Although prior studies have extensively examined misconceptions, mental models, and learning difficulties in astronomy education, most investigations treat these aspects separately. Research that integrates cognitive-process profiling, mental-model categorization, and learning-interest analysis within a single empirical framework remains limited, so learning materials are often designed based on generalized assumptions rather than empirically derived learner profiles.

The novelty of this study lies in its integrated diagnostic approach, which combines Rasch-based cognitive process measurement, qualitative mental model classification, and learning interest profiling to construct a more comprehensive picture of students' readiness to learn moon phase concepts.

Accordingly, this study examined three interrelated dimensions of first-year undergraduate students' understanding of moon phases: cognitive processes, mental models, and learning interest. Two research questions guided the study: (1) What are the characteristics of students' cognitive processes (C3–C5), mental models, and learning interest in moon phase concepts? Moreover, (2) How can cognitive processes, mental models, and learning interest be integrated to construct a diagnostic learner profile of students' readiness in learning moon phase concepts? By answering these questions, the study contributes an empirically grounded characterization of learners that can inform the design of differentiated and adaptive astronomy instruction.

METHOD

Research Design

This study employed a convergent mixed-methods design, in which quantitative and qualitative data were collected concurrently, analyzed separately, and then integrated to develop an integrated interpretation. The quantitative strand described students' cognitive performance and learning interest and examined the psychometric quality of the cognitive process test through Rasch analysis. The qualitative strand interpreted students' written explanations and interview responses to characterize their mental models. This design was chosen because the three dimensions cognitive readiness, conceptual representation, and motivation are conceptually complementary, and integrating them yields a more complete profile of learners than any single strand alone. The study was descriptive and diagnostic; it did not test any instructional intervention. Figure 1 summarizes the design.

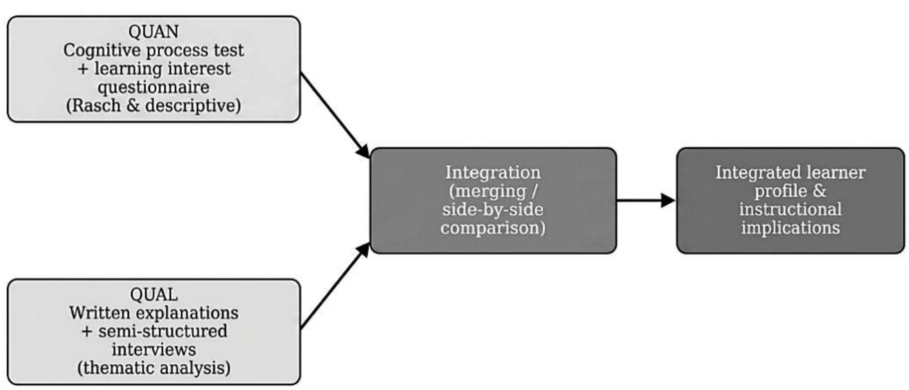

Figure 1. Convergent mixed methods design used to profile learners.

Participants and setting

The study was conducted at Universitas Pendidikan Indonesia, Bandung, Indonesia. Participants were 65 first-year undergraduate students (51 female, 14 male; aged 18–20 years) enrolled in a physics-related course during their first semester, in which moon phases were a topic of study. Participants were selected through purposive sampling based on their enrolment in the relevant course. Inclusion criteria were active enrolment, completion of both the cognitive process test and the learning interest questionnaire, and provision of complete responses; cases with incomplete data were excluded. The gender distribution reflects the composition of the physics education cohort and is acknowledged as a contextual characteristic of the sample. Table 1 presents the participant characteristics.

Table 1. Characteristics of participants

No	Gender	Frequency	Age (years)
1	Female	51	18–20
2	Male	14	18–20
	Total	65	

Instruments

Three instruments were used: a cognitive-process test, a learning interest questionnaire, and a semi-structured interview guide. The cognitive process test comprised eight constructed-response items aligned with the revised Bloom's taxonomy at levels C3 (apply), C4 (analyze), and C5 (evaluate) (Anderson & Krathwohl, 2001), with three items at C3, three at C4, and two at C5. Each item required a constructed response so that both the correctness of the answer and the quality of the underlying reasoning could be examined. The item blueprint is presented in Table.

Table 2. Blueprint of the cognitive process test

Item	Code	Level	Targeted conceptual indicator (moon phases)
1	A1	C3 – Apply	Identifying the lunar phase for a given Sun-Earth-Moon configuration
2	A2	C3 – Apply	Applying the illumination concept to determine the illuminated fraction
3	S	C3 – Apply	Relating the observer's viewpoint to the phase seen from Earth
4	T	C4 – Analyze	Analyzing the spatial relationship within the Sun-Earth-Moon system
5	A3	C4 – Analyze	Comparing two configurations to infer the resulting phase change
6	CE1	C4 – Analyze	Interpreting a diagram to detect an inconsistent representation
7	CE2	C5 – Evaluate	Evaluating the correctness of a given explanation of a phase
8	A4	C5 – Evaluate	Judging which of two alternative representations is scientifically valid

The same constructed responses provided the basis for inferring students' mental models. Written explanations were analyzed to classify conceptual understanding into Initial, Synthetic, and Scientific categories, consistent with the conception of mental models as internal cognitive representations used to explain and reason about phenomena (Greca & Moreira, 2000; Vosniadou, 2008, 2011). The learning interest questionnaire used a Likert scale to measure attention, curiosity, enthusiasm, and engagement in learning moon phases (Hidi & Renninger, 2006). Total scores were categorized as low, moderate, or high interest. The semi-structured interview guide was used to validate and deepen the interpretation of mental models, with questions probing students' understanding of lunar illumination, the changing appearance of the Moon, and the spatial relationships among celestial bodies, since conceptual understanding cannot be captured fully by test scores alone (Treagust & Duit, 2008).

Data Collection Procedure

Data collection proceeded in four stages. First, instruments were prepared by mapping conceptual indicators of moon phases onto the revised Bloom's taxonomy (C3–C5). Second, participants were selected by purposive sampling and informed of the study's purpose and data requirements. Third, quantitative data were collected as students completed the cognitive process test and the learning interest questionnaire; responses were organized by item code and cognitive level. Fourth, qualitative data were collected and validated: students' written explanations were analyzed for conceptual patterns and then clarified through semi-structured interviews to confirm the mental model classification.

Prior to data collection, the instruments were evaluated by experts to establish content validity. The cognitive process test, learning-interest questionnaire, and semi-structured interview guide were reviewed by three experts in physics education, astronomy learning, and educational assessment. The experts examined the relevance of each item to the targeted indicators, the clarity of wording, the appropriateness of cognitive levels based on the revised Bloom's taxonomy, and the suitability of the items for first-year undergraduate students. Revisions were made based on the experts' suggestions before the instruments were administered to the 65 participants.

The sample size was considered adequate for the diagnostic purpose of this Rasch analysis. Linacre (1994) suggested that a well-targeted sample of approximately 50 respondents can yield useful and stable Rasch estimates within about ±1 logit, while the minimum sample size may range from 27 to 61, depending on person-item targeting. Therefore, the use of 65 students in this study was considered acceptable for exploratory and diagnostic profiling. However, the moderate person separation found in this study was interpreted with caution, as it may also reflect the limited number of items in the eight-item cognitive process test.

Data Analysis

Quantitative data were analyzed using descriptive statistics and the Rasch model. Descriptive analysis summarized students' performance across the three cognitive levels (C3, C4, C5) and the distribution of learning interest. The Rasch model, implemented in Winsteps 5.11.0.0, was used to evaluate item fit, item difficulty, reliability, and separation, placing person ability and item difficulty on a common logit scale (Sumintono, B., & Widhiarso, 2014; Wright & Masters, 1982). Cognitive performance is reported both as the mean score at each cognitive level and as person ability on the logit scale, so that the descending C3–C5 pattern can be examined directly.

Qualitative data from written responses and interviews were analyzed thematically. Coding was based on six indicators: conceptual accuracy, causal reasoning, spatial reasoning, representational consistency, presence of misconceptions, and coherence of explanation. Two researchers independently coded all responses and classified each student into one of the three mental model categories. Coding discrepancies were resolved through discussion until consensus was reached, and a subset of cases was cross-checked by a third experienced rater to strengthen the trustworthiness of the classification (Greca & Moreira, 2000; Syuhendri et al., 2022; Vosniadou, 2011). Finally, the quantitative and qualitative findings were merged using an individual profile matrix. Each student was assigned a profile record containing cognitive performance scores, Rasch-based ability information, learning-interest category, and mental-model classification. These individual profiles were then tabulated and compared across dimensions to identify patterns of alignment or discrepancy among cognitive processes, conceptual understanding, and learning interest. For example, students with high learning interest but Initial or Synthetic mental models were interpreted as having motivational readiness but limited conceptual readiness. This merging procedure enabled the construction of an integrated diagnostic learner profile rather than separate interpretations of quantitative and qualitative results.

For integrated visualization, individual profiles were aggregated by cross-tabulating learning-interest categories with mental-model classifications. The resulting proportions were presented using a 100% stacked bar chart to illustrate the relationship between motivational readiness and conceptual understanding.

Ethical considerations

Participation was voluntary and based on informed consent. Students were informed of the study's purpose, the voluntary nature of participation, and their right to withdraw without consequence. All responses were anonymized prior to analysis, and the data were used solely for research purposes in accordance with the institution's ethical guidelines for research involving human participants.

RESULT AND DISCUSSION

The results characterize first-year undergraduate students' learning needs in moon phases by integrating three dimensions: cognitive processes, mental models, and learning interest. The analysis began with Rasch validation of the cognitive process test, after which cognitive performance was interpreted together with the mental model categories and the learning interest profile to form an integrated picture of learning readiness.

Psychometric Quality of the Cognitive Process Test

The eight-item cognitive process test represented the revised Bloom's taxonomy levels C3-C5. Rasch analysis examined person and item measures, item statistics, reliability, and separation (Table 3).

Table 3. Summary of person and item statistics from the Rasch analysis

Component	Mean measure	SD measure	Infit MNSQ	Outfit MNSQ	Interpretation
Person	0.88 logits	1.09	1.01	0.99	Good model fit
Item	0.00 logits	0.97	1.00	0.99	Valid measurement structure

The mean person measure of 0.88 logits indicates that students' average ability was slightly above the mean item difficulty, which is conventionally fixed at 0.00 logits, so the instrument was well targeted to the respondents while still capturing variability in performance. Person fit statistics (Infit MNSQ = 1.01; Outfit MNSQ = 0.99) indicate response patterns consistent with model expectations. Item statistics likewise indicated sound properties: the mean item measure was 0.00 logits (SD = 0.97), and item fit ranged from 0.65 to 1.27 for both Infit and Outfit MNSQ, within acceptable thresholds. Reliability and separation indices are reported in Table 4.

Item reliability of 0.96–0.97 and item separation above 5.00 indicate a stable difficulty hierarchy and high capacity to distinguish difficulty levels. Person reliability of 0.73–0.79 and Cronbach's alpha (KR-20) of 0.76 indicate

Table 4. Reliability and separation indices of the cognitive process test

Index	Person	Item	Interpretation
Reliability (Real)	0.73	0.96	Acceptable person, excellent item reliability
Reliability (Model)	0.79	0.97	Acceptable person, excellent item reliability
Separation (Real)	1.64	5.15	Moderate person, high item separation
Separation (Model)	1.94	5.44	Good person, high item separation
Cronbach's alpha (KR-20)	0.76	–	Acceptable internal consistency

acceptable internal consistency. The person separation of 1.64 (Real) suggests that the test reliably distinguishes roughly two strata of ability; this is a known limitation of short instruments and indicates that adding items would improve precision across a wider ability range. Overall, the test is sufficiently valid and reliable for profiling cognitive processes, with this constraint acknowledged.

Item Difficulty and Person-Item Targeting

Person-item targeting on the common logit scale showed that most students were located between 0 and 2 logits, reflecting a moderate level of cognitive readiness, and that several items fell within this range, indicating a reasonable match between item difficulty and the sample's general ability. The two most difficult items, CE1 and T, were located above most students' ability level. At the same time, items S and CE2 were also relatively demanding because they required higher-order processing, particularly the analysis and evaluation of lunar phenomena. This pattern indicates that C4 and C5 tasks remained challenging for most students. Rather than signaling item weakness, the elevated position of these items has diagnostic value: it identifies the reasoning tasks that currently exceed students' readiness and that instruction should explicitly support through scaffolding, visual representation, guided reasoning, and formative feedback.

Cognitive Process Profile

Cognitive performance showed a consistent descending trend from C3 (apply) to C5 (evaluate). As summarized in Figure 2, students performed best on application tasks and progressively less well on analysis and evaluation tasks.

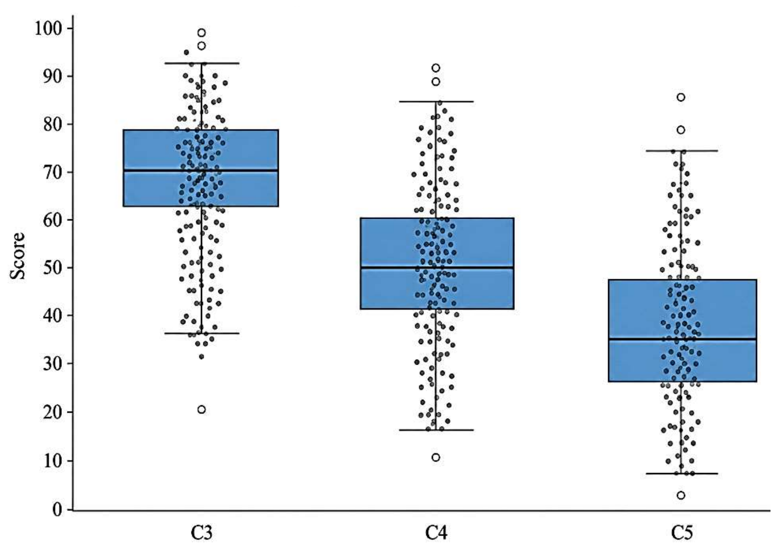

Figure 2. Distribution of students' cognitive performance across C3, C4, and C5 levels

Figure 2 presents the distribution of students' cognitive performance across the three cognitive levels. The distributions show a progressive downward shift from C3 to C4 and C5, indicating that students performed better when applying familiar concepts than when analyzing spatial relationships or evaluating scientific explanations. In the context of moon phases, the lower performance at C4 and C5 reflects students' difficulties in integrating the relative positions of the Sun, Earth, and Moon, interpreting the observer's perspective, and evaluating alternative explanations of lunar phenomena. The variability within each level also indicates that students differed in their cognitive readiness. However, the overall pattern consistently shows that higher-order cognitive tasks were more challenging tha application tasks.

This pattern indicates that students' difficulties are associated less with factual recall than with higher-order cognitive demands, since moon phase concepts require integrating visuospatial reasoning, causal explanation, and three-dimensional relationships among celestial bodies (Bryce & Blown, 2012; Plummer, 2014). The lower performance at C4 and C5 therefore highlights the need for instructional scaffolding that progressively supports learners from application toward analysis and evaluation (L. W. Anderson & Krathwohl, 2001; Arslan & Durikan, 2016; Ubben & Bitzenbauer, 2022).

This suggests that students are more proficient in applying basic concepts than in analyzing relationships or evaluating scientific explanations. In the context of moon phase learning, this means that students can generally identify lunar phases or apply familiar concepts in routine situations, but encounter difficulties when required to interpret spatial relationships among the Sun, Earth, and Moon or critically evaluate alternative scientific explanations.

The distribution of students' scores further supports this pattern. Most students scored 3-5 on a 0-10 scale, indicating low to moderate conceptual understanding. Only a small proportion of students achieved higher scores, suggesting that advanced conceptual readiness is limited within the cohort.

These findings indicate that students' difficulties in understanding moon phases are not limited to factual recall but are strongly associated with higher-order cognitive demands. Moon phase concepts require integrating visuospatial reasoning, causal explanation, and three-dimensional spatial relationships among celestial bodies (Bryce & Blown, 2012; Plummer, 2014; Tapalova & Zhiyenbayeva, 2022; Vergara et al., 2024). The lower performance observed at the C4 and C5 levels therefore highlights the necessity of instructional scaffolding that progressively supports learners from conceptual application to the analysis and evaluation of astronomical phenomena (Anderson et al., 2024; Arslan & Durikan, 2016; Ubben & Bitzenbauer).

Learning Interest Profile

Students' learning interest was categorized as low, moderate, or high (Figure 3).

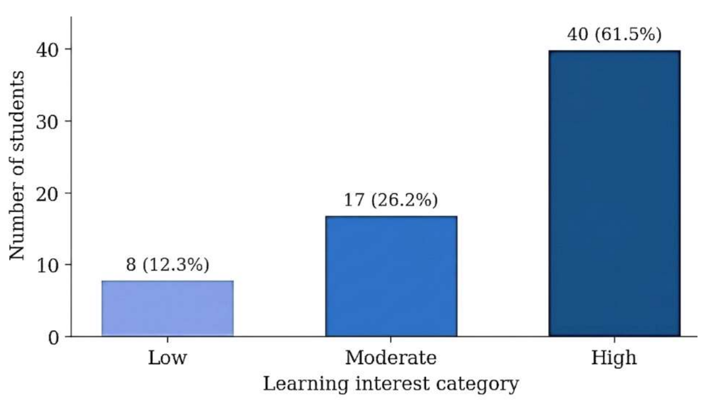

Figure 3. Distribution of students' learning interest across categories

The distribution was positively skewed towards higher interest: most students (61.5%) reported high interest, followed by moderate (26.2%) and low (12.3%) interest. This indicates generally positive attitudes, curiosity, and willingness to engage with moon phase concepts, providing a supportive affective foundation for engaging with abstract, spatially complex content. At the same time, students in the moderate and low categories exhibit variability in motivational readiness, so differentiated strategies remain necessary. When this profile is read against the cognitive results, a clear discrepancy emerges: despite high interest, performance was concentrated at low to moderate levels, especially in C4 and C5. High interest should therefore be interpreted as an entry condition for engagement rather than as an indicator of conceptual mastery.

Mental Model Profile

Mental models were classified using the six analytical indicators introduced above. Conceptual accuracy refers to correctly understanding that moon phases result from the relative positions of the Sun, Earth, and Moon and from the illuminated proportion of the Moon, causal reasoning captures explaining the underlying causes of the changing appearance, spatial reasoning reflects interpreting three dimensional relationships among the Sun, Earth, Moon, and observer, representational consistency concerns alignment between verbal explanations and visual representations, misconception identification captures non scientific explanations such as Earth's shadow, cloud obstruction, or the Moon as a self luminous body and coherence reflects the logical structure and internal consistency of the explanation. The resulting categories are summarized in Table 5.

As shown in Figure 4, the Synthetic model was dominant (50.8%), followed by the Initial model (40.0%) and the Scientific model (9.2%). The large Initial group indicates that a substantial proportion of learners still require foundational conceptual support; these students tended to rely on intuitive or inaccurate explanations, such as attributing moon phases to Earth's shadow or to intrinsic changes in lunar illumination, pointing to the need for instruction that explicitly confronts misconceptions and supports conceptual reconstruction through structured visual and spatial representations. The dominant Synthetic group reflects a transitional stage in which scientific elements, such as the role of sunlight, are partially integrated, but causal and spatial reasoning remain unstable. The small Scientific group (9.2%) constructed coherent explanations grounded in the interaction among sunlight, lunar position, and observer perspective; rather than basic instruction, these students benefit from enrichment tasks involving evaluative reasoning and complex representations.

Table 5. Criteria for mental model categorization

Category	Main characteristics	Indicators
Initial	Explanation dominated by intuitive or incorrect ideas	Low conceptual accuracy, weak causal reasoning, limited spatial reasoning, visible misconceptions
Synthetic	Partial scientific understanding that remains incomplete or inconsistent	Some correct concepts present, but reasoning not fully coherent and misconceptions may persist
Scientific	Coherent, accurate, scientifically consistent explanation	Strong conceptual accuracy, clear causal reasoning, consistent spatial reasoning, no dominant misconception

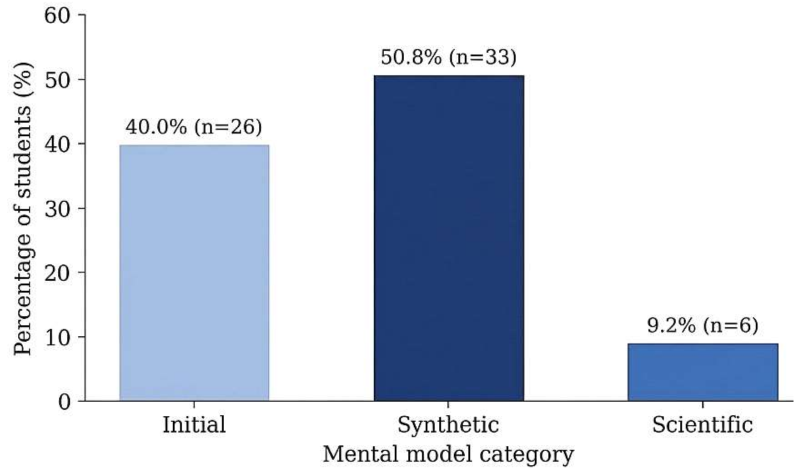

Figure 4. Distribution of students' mental models in moon phase concepts

The semi-structured interviews corroborated this classification. For example, a student classified as holding a Synthetic model correctly invoked sunlight yet retained a shadow-based misconception:

"I think the Moon looks different because only one side gets light from the Sun. But maybe the dark part is because the Earth blocks the light, so from Earth we only see some part of the Moon." (Student S-23, Synthetic model)

Similarly, an Initial model response was characterized by non-scientific causal reasoning and everyday perception:

"Sometimes the Moon looks full, sometimes it looks like a crescent. I think the shape might change because of the clouds or because we see it from different places. I am not really sure about the position of the Sun and Earth." (Student S-11, Initial model)

Another Synthetic model response showed partial scientific understanding but was still mixed with alternative conceptions:

"The Moon phase happens because the Moon moves around the Earth, and the Sun gives light to the Moon. But I still get confused why the lighted part can become half or crescent. Maybe it depends on how far the Moon is from the Earth." (Student S-35, Synthetic model)

In contrast, a Scientific model response demonstrated coherent integration of illumination geometry and orbital motion:

"The phase depends on the position of the Moon compared with the Earth and the Sun. If the Moon keeps moving, the part that is lit by the Sun looks different from our view on Earth." (Student S-08, Scientific model)

Another Scientific model response further reinforced this structurally consistent explanation:

"Waxing and waning phases are determined by the changing angle between the Sun, Earth, and Moon. The visible illuminated fraction changes systematically as the Moon completes its orbit." (Student S-19, Scientific model)

These findings indicate that students' conceptual understanding of moon phases is characterized by incomplete integration of scientific knowledge. Mental models function as internal cognitive structures that guide explanation and prediction (Assem et al., 2023; Greca & Moreira, 2000; Özcan & Bezen, 2016; Unal et al., 2014). And the progression from Initial through Synthetic to Scientific reflects a gradual process of conceptual restructuring that requires targeted instructional support (Treagust, 2008; Vosniadou, 2008). Consequently, instruction should aim not only to correct answers but to restructure the reasoning and conceptual frameworks that underlie them.

Integration of the Three Dimensions

The integration of cognitive processes, mental models, and learning interest provides a more comprehensive diagnostic profile of students' learning readiness in moon phase concepts. To visualize the relationship between motivational readiness and conceptual understanding, the distribution of mental models was examined across different levels of learning interest (Figure 5).

Figure 5 presents the distribution of students' mental models within each learning-interest category. The percentages were calculated separately for the Low, Moderate, and High interest groups, ensuring that each stacked

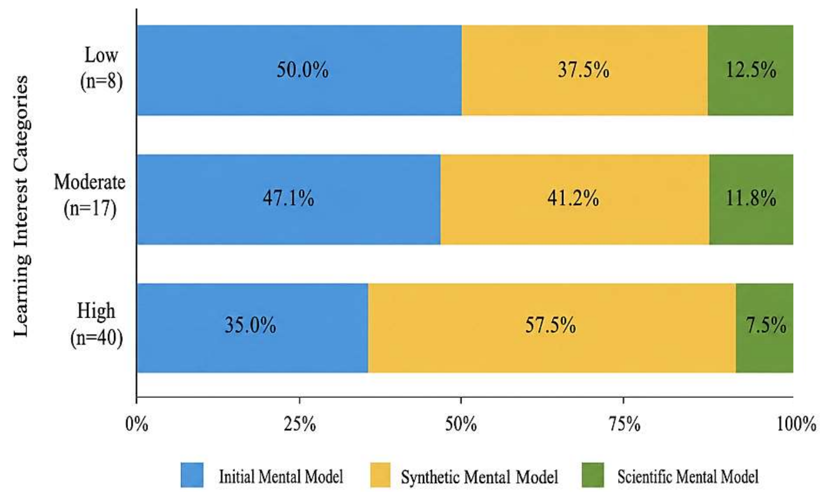

Figure 5. Integrated distribution of mental models across learning interest categories

bar represents 100% of students in its category. The validated distribution shows whether stronger learning interest is accompanied by a more scientifically coherent mental model. The continued presence of Initial and Synthetic models, particularly among students with moderate or high learning interest, indicates that motivational readiness does not necessarily correspond to conceptual mastery. Students may demonstrate curiosity and a willingness to engage with moon-phase concepts while still exhibiting incomplete causal reasoning, difficulties interpreting Sun–Earth–Moon spatial relationships, or misconceptions about Earth's shadow. Accordingly, learning interest should be interpreted as a foundation for engagement rather than direct evidence of scientific understanding.

Therefore, learning interest should be interpreted as a condition that supports engagement rather than as direct evidence of conceptual mastery. Students with high interest but Synthetic mental models represent a particularly important diagnostic profile: they are motivated to engage with astronomical concepts but require instructional support to transform partial understanding into scientifically coherent explanations. This finding emphasizes the importance of integrating motivational, cognitive, and conceptual dimensions when designing differentiated astronomy instruction. Aligning instruction with learners' readiness, conceptual structures, and interests is consistent with the principles of differentiated instruction (Tomlinson et al., 2017), and adaptive learning environments can strengthen this alignment by dynamically adjusting content, feedback, and task complexity to individual characteristics (Kaharu & Mansyur, 2021; Rohadi & Setiawan, 2020; Roll & Ford, 2016; Vergara et al., 2024). Table 6 translates the empirical findings into concrete instructional design implications.

Taken together, these findings show that students' learning needs extend beyond content delivery and require structured support aligned with their cognitive and conceptual profiles. Analysis and evaluation should be developed through a sequence of phase identification, spatial analysis, and explanation evaluation tasks. Students with Initial models need explicit comparison between ordinary phase geometry and lunar-eclipse geometry. In contrast, students with Synthetic models need a guided comparison between an Earth-shadow explanation and a 3D observer-perspective simulation. Students with Scientific models need transfer tasks involving unfamiliar configurations and flawed representations. High learning interest can be sustained through observation logs and interactive

Table 6. From empirical findings to instructional design implications

Profile finding	Learning need	Instructional-design implication
Declining performance from C3 to C5	Higher-order cognitive support	Sequence tasks from identifying the phase in a given Sun–Earth–Moon configuration, to explaining changes in the visible illuminated fraction, and finally to evaluating two competing explanations using illumination geometry.
High-difficulty items (CE1, T)	Prerequisite strengthening	Use a lamp as the Sun, a globe as Earth, and a sphere as the Moon. Model several observer positions, provide worked examples, and ask students to identify inconsistent phase diagrams before completing independent analysis.
Initial mental model	Conceptual restructuring	Elicit the Earth shadow misconception, then compare ordinary moon-phase geometry with lunar eclipse geometry using the lamp globe sphere model. Require students to explain why Earth's shadow does not cause ordinary phases.
Synthetic mental model	Concept integration	Ask students to visually compare an Earth-shadow model with a 3D simulation showing the illuminated Moon from an observer's perspective on Earth. Require a revised explanation that links sunlight, orbital position, and the visible illuminated fraction.
Scientific mental model	Advanced enrichment	Assign unfamiliar Sun–Earth–Moon configurations, ask students to predict the observed phase, critique a flawed diagram, and justify waxing or waning from more than one observer perspective.
High learning interest	Sustained engagement	Use a four-week Moon observation log linked to an interactive simulation. Ask students to match observations to predicted configurations and provide immediate feedback when observations and models disagree.

simulations, but feedback must remain focused on conceptual accuracy.

To illustrate the integrated diagnostic profile, a representative learner with high learning interest but a Synthetic mental model can be considered. This student demonstrates strong curiosity and engagement with moon phase concepts, but their conceptual understanding remains partially inconsistent. In a C3 (apply) task, the student may successfully identify the Moon phase from a given Sun-Earth-Moon configuration by recalling previously learned patterns or applying basic concepts. However, in a C5 (evaluate) task requiring judgment of competing explanations, the student may struggle to evaluate scientific reasoning and still retain misconceptions, such as explaining moon phases through the Earth's shadow despite recognizing that sunlight influences lunar appearance. This response indicates that the student has acquired some scientific elements but has not yet constructed a coherent causal and spatial understanding of the Sun-Earth-Moon system.

This profile demonstrates that high learning interest represents motivational readiness rather than direct evidence of conceptual mastery. Therefore, instructional support for such learners should focus not on increasing engagement but on strengthening conceptual integration through visual-spatial representations, guided analysis of celestial configurations, and targeted feedback on misconceptions. By combining cognitive process performance, mental model classification, and learning interest, the integrated diagnostic profile provides a more precise basis for differentiated instruction because students with similar motivation levels may require different forms of conceptual support.

Limitations

Several limitations should be noted. The sample comprised 65 first-year students from a single institution selected through purposive sampling, and the gender distribution was uneven. The findings are therefore analytically rather than statistically generalizable and should be interpreted as a contextual profile rather than a population estimate. The cognitive process test contained only eight items, which yielded moderate person separation; expanding the item pool would improve measurement precision. Finally, the study was descriptive and diagnostic and did not test any instruction; the design implications in Table 8 are hypotheses for instructional design that future studies should implement and evaluate.

■ CONCLUSION

This study contributes to the astronomy education literature by proposing an integrated diagnostic learner-profiling framework that combines cognitive processes, mental models, and learning interest as empirical foundations for adaptive differentiated learning. The integration of Rasch measurement and qualitative analysis provides a comprehensive understanding of students' readiness in learning moon phase concepts, not only through cognitive performance but also through the conceptual structures and affective tendencies underlying their explanations.

The findings show that students' difficulties are associated with fragmented reasoning, incomplete mental models, and a gap between high learning interest and limited cognitive conceptual development. Thus, learning interest should be understood as a condition that supports engagement rather than as direct evidence of conceptual mastery. These results emphasize the need for astronomy instruction based on diagnostic learner profiles and that supports conceptual reconstruction, visuospatial reasoning, and higher-order cognitive processes.

The present study does not claim to have developed or tested an adaptive differentiated learning module. Instead, it provides empirical design principles for future instructional development, including cognitive scaffolding, misconception-focused feedback, guided reasoning, interactive visualization, and enrichment activities. Future research should develop and evaluate adaptive differentiated astronomy instruction based on these integrated learner profiles in authentic classroom contexts. The integrated learner profiles established in this study provide a theoretical and empirical foundation for adaptive astronomy instruction that addresses diverse learner characteristics.

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DECLARATION OF GENERATIVE AI USAGE IN THE WRITING PROCESS

Declaration of AI-Assisted Technology Use: During the preparation of this manuscript, the authors used a generative AI tool only to support language refinement and stylistic improvement. After using this tool, the authors carefully reviewed, revised, and edited the manuscript as necessary. The scientific content, data processing, analysis, interpretation, and conclusions were developed, validated, and approved entirely by the authors. The authors take full responsibility for the accuracy, integrity, originality, and content of the published manuscript.

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