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A Phenomenographic Study of Students' Experiences and Understanding in Learning the Solar System through the Digital Media "Solar System Exploration"

Bella Merryzca Purnama[1], Wahono Widodo[2], Suryanti[3], Nafi Isbadrianingtyas[4]
[1,2,3,4]Fakultas Ilmu Pendidikan Universitas Negeri Surabaya

[*]Email Korespodensi: 25010855177@mhs.unesa.ac.id

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ABSTRACT

The integration of digital technology in elementary education has created new opportunities for supporting students' conceptual understanding in Science and Social Studies (IPAS) learning. However, previous studies have predominantly focused on measuring the effectiveness of digital media rather than examining how conceptual understanding is formed through students' learning experiences. This study aimed to explore the process through which conceptual understanding develops within a digital exploration space during solar system learning in elementary school. This study employed a qualitative phenomenographic design involving one classroom teacher and twelve Phase C students at an elementary school in Indonesia. Data were collected through participant observation, semi-structured interviews, and document analysis. The data were analyzed using thematic analysis following Braun and Clarke's procedures, while trustworthiness was established through triangulation, member checking, and audit trails. The findings revealed that conceptual understanding was formed through four interconnected stages: digital visualization, active exploration, social negotiation, and reflective integration. Digital visualization enabled students to transform abstract astronomical concepts into concrete mental representations. Active exploration encouraged students to construct meaning independently through interaction with digital resources. Social negotiation facilitated conceptual refinement through discussion and collaborative inquiry, while reflective integration supported the development of deeper conceptual connections among scientific phenomena. These processes collectively shifted students' understanding from rote memorization toward relational and meaningful conceptual understanding. This study contributes a conceptual model explaining how digital exploration spaces function as socio-cognitive learning environments that support conceptual understanding in elementary IPAS learning. The findings provide practical implications for designing technology-enhanced learning experiences that promote exploration, dialogue, and reflection rather than merely delivering information.

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JURAGAN
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INTRODUCTION

The rapid advancement of digital technology has transformed educational practices and reshaped how students interact with knowledge. In elementary education, digital tools such as interactive videos, simulations, QR codes, and multimedia resources are increasingly integrated into classroom learning to support student engagement and independent exploration. This transformation is particularly relevant to Integrated Science and Social Studies (IPAS), which requires students not only to acquire information but also to develop meaningful conceptual understanding (Rahmawati & Fitriani, 2023). However, the availability of digital resources does not necessarily guarantee deep learning. Students often demonstrate the ability to access and recall information quickly, yet they experience difficulties in explaining relationships among concepts, interpreting scientific phenomena, and applying their understanding in different contexts.

These challenges are evident in the learning of the solar system, one of the fundamental topics in elementary IPAS. The solar system contains abstract concepts because most celestial objects and phenomena cannot be directly observed by students. Consequently, learners frequently rely on symbolic representations, images, and verbal explanations to construct their understanding (Ferguson et al., 2023). Preliminary observations conducted in an elementary classroom revealed that many students were able to memorize the sequence of planets but struggled to explain planetary characteristics, interactions among celestial bodies, and phenomena occurring within the solar system. Teachers also reported that instruction often depended on static two-dimensional images contained in textbooks, limiting opportunities for students to visualize scientific concepts comprehensively.

From a constructivist perspective, conceptual understanding develops through active engagement and meaning-making rather than through passive information reception. Students build knowledge by interacting with learning environments, connecting new information with prior experiences, and reflecting on their observations (van der Linden & McKenney, 2020). Therefore, learning environments that provide opportunities for exploration, visualization, and inquiry are essential for supporting conceptual development, particularly when students encounter abstract scientific concepts (Rolfes et al., 2020).

Recent studies have demonstrated the educational potential of digital technology in science learning. Muspiroh et al. (2025) found that Augmented Reality-based learning media improved students' understanding of scientific concepts that are difficult to observe directly. Likewise, Muntaqiyah et al. (2025) reported that digital pop-up books enhanced elementary students' conceptual understanding and critical thinking skills. These findings suggest that digital learning environments can facilitate the visualization of abstract phenomena and increase students' engagement with learning content. However, although digital media have demonstrated positive effects on students' conceptual outcomes, many implementations still emphasize technological affordances and content presentation rather than examining how students construct meaning from their learning experiences and transfer understanding into deeper conceptual thinking (Fawns, 2022). As a result, a gap remains between the expectation that digital learning environments will automatically foster meaningful understanding and the reality that students may remain focused on recalling information instead of developing transferable conceptual knowledge. This issue becomes particularly relevant in elementary science learning, where understanding abstract topics requires not only visual support but also purposeful learning experiences that connect prior knowledge, inquiry, interpretation, and reflection.

Beyond technological integration, this study proposes the Understanding by Design (UbD) framework as an alternative approach for addressing the identified gap. The Understanding by Design

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JURAGAN
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(UbD) framework has gained increasing attention as an approach for promoting meaningful learning. UbD emphasizes the development of enduring understanding through backward design, authentic learning experiences, and performance-based assessment. Fradina et al. (2022) reported that UbD-based learning improved conceptual mastery and problem-solving abilities. Similarly, Pratiwi and Yuliana (2025) demonstrated the validity and effectiveness of instructional materials developed using the UbD framework. These studies indicate that UbD provides a promising foundation for designing learning experiences that foster deep understanding rather than superficial knowledge acquisition.

Prior to the present investigation, the researchers developed and implemented a digital learning environment and instructional materials based on the Understanding by Design (UbD) framework for elementary IPAS learning on the topic of the solar system. The learning design integrated digital exploration activities, interactive visual resources, inquiry tasks, and reflective learning experiences to support meaningful conceptual understanding. Initial implementation results demonstrated encouraging outcomes. Students' average scores increased from 70 in the pretest to 90 in the posttest, resulting in an N-gain score of 0.67, which indicates a moderate improvement in conceptual understanding. These findings suggest that the developed UbD-oriented digital learning environment successfully supported students' conceptual achievement and met the expected instructional objectives.

However, although the quantitative results confirmed improvements in learning outcomes, they did not fully explain how such conceptual changes occurred. The increase in scores provided limited insight into what students experienced during learning, how they interpreted digital exploration activities, which learning experiences influenced their understanding, and what changes they perceived in their ways of thinking about the solar system. Questions also remained regarding how students connected prior knowledge with newly explored information, constructed meaning, and developed deeper conceptual understanding throughout the learning process. Therefore, further qualitative investigation was considered necessary to explore students' experiences, perceptions, and meaning-making processes in order to understand not only whether conceptual improvement occurred, but also how and why conceptual understanding was formed.

Despite these contributions, existing studies predominantly evaluate digital media and instructional approaches through quantitative measures such as learning achievement, conceptual gain scores, or instructional effectiveness (Kümmel et al., 2020). While such findings provide evidence of educational impact, they offer limited insight into how conceptual understanding is actually constructed during learning (Hunter et al., 2021). The processes through which students explore digital resources, interpret information, negotiate meaning, and connect ideas remain insufficiently examined. Furthermore, research investigating conceptual understanding formation through digital exploration activities within elementary IPAS learning contexts remains limited, particularly on the topic of the solar system (Putra & Nandiyanto, 2022).

Beyond methodological limitations, another concern relates to the limited representation of students' perspectives within the existing literature, where students' voices are often underrepresented and participation tends to remain consultative rather than providing insight into how learners interpret and construct meaning from educational experiences (Gillett-Swan & Baroutsis, 2024). Most studies emphasize learning outcomes, whereas students' experiences, reflections, interpretations, and interactions during the learning process receive comparatively less attention (Schmid et al., 2024). As a result, the mechanisms underlying conceptual understanding formation are not yet fully understood. This gap highlights the need for qualitative investigations that capture students' experiences as they engage with digital learning environments.

eISSN 3063-802X & pISSN 3063-8011
JURAGAN
JURNAL RAGAM PENGABDIAN - PENELITIAN

The scientific novelty of this study lies in examining how elementary students construct conceptual understanding through lived experiences within a UbD-oriented digital exploration environment for solar system learning. By integrating constructivist learning theory and Understanding by Design, this study provides a process-oriented perspective on conceptual learning that extends beyond achievement-based evaluation. By combining perspectives from constructivist learning theory and Understanding by Design, the study provides a process-oriented understanding of conceptual learning that extends beyond achievement-based evaluation. Based on the identified gap, the research problem addressed in this study is: How do elementary students construct conceptual understanding through engagement in a UbD-oriented digital exploration space during solar system learning?

Therefore, this study aims to explore how conceptual understanding is formed through students' engagement in a digital exploration space during solar system learning in elementary school. Using a qualitative approach, this study seeks to examine students' learning experiences, meaning-making processes, and social interactions that contribute to conceptual understanding. The findings are expected to contribute to the development of constructivist learning theory, Understanding by Design, and conceptual understanding research in elementary science education, while also providing practical implications for teachers and curriculum developers in designing meaningful, exploratory, and understanding-oriented learning experiences.

METHOD

This study employed a qualitative approach using a phenomenography design to explore how elementary students develop conceptual understanding through digital exploration activities in IPAS learning on the topic of the solar system. The study was conducted through five phases: preparation, data collection, data analysis, validation, and reporting. The preparation phase involved preliminary observation and the design of digital exploration learning.

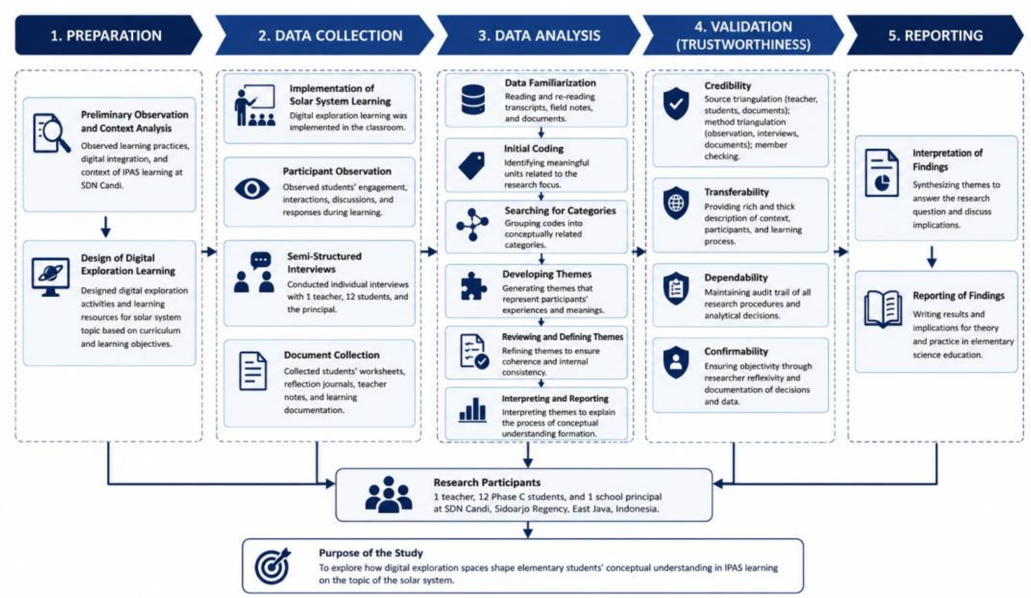

Figure 1. Research Flow of the Study

Data collection consisted of classroom implementation, participant observation, semi-structured

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JURAGAN
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interviews, and document collection. Data were then organized and analyzed using thematic analysis following Braun and Clarke (2021). Trustworthiness was established through triangulation and member checking before interpretation and reporting of findings. The overall research procedure is presented in Figure 1.

A phenomenography was selected because it enables an in-depth investigation of a phenomenon within its real-life educational context, allowing the researcher to examine students' learning experiences, social interactions, and meaning-making processes holistically. The study focused on understanding the formation of conceptual understanding rather than measuring causal relationships or determining the effectiveness of instructional media.

The research was conducted at SDN Candi, Sidoarjo Regency, East Java, Indonesia, an elementary school implementing the Merdeka Curriculum and integrating digital technology into classroom learning. The study involved one classroom teacher, twelve Phase C students who participated in the entire solar system learning sequence, and the school principal as a supporting informant. Participants were selected through purposive sampling based on their direct involvement in the learning activities and their ability to provide rich information regarding the phenomenon under investigation. The inclusion criteria required participants to actively engage in solar system learning, participate in all digital exploration activities, voluntarily agree to participate in the study, and obtain parental consent for interview participation. Participant recruitment continued until sufficient information richness was achieved and no substantially new insights emerged from the data.

The researcher served as an observer-participant throughout the study while maintaining the natural learning environment. Data were collected through participant observation, semi-structured interviews, and document analysis. Participant observation was conducted during classroom learning activities to examine students' engagement, interactions, collaborative discussions, and responses while exploring digital learning resources. Observational data were recorded in field notes and structured observation sheets. Semi-structured interviews were conducted individually with students and the classroom teacher to explore their experiences, perceptions, and interpretations of digital exploration activities and conceptual learning. Each interview lasted approximately 20–40 minutes, was audio-recorded, and subsequently transcribed verbatim for analysis. Document analysis was performed on students' worksheets, reflective journals, classroom artifacts, teacher notes, and learning documentation to complement and corroborate findings from observations and interviews.

The primary learning environment investigated in this study was a digital exploration space designed to support solar system learning. The learning environment integrated digital resources, including QR-code-based materials, interactive visual content, exploration activities, and collaborative discussions. These resources provided opportunities for students to independently access information, visualize abstract astronomical concepts, engage in peer interaction, and reflect upon their learning experiences.

Data were analyzed using thematic analysis following the framework proposed by Braun and Clarke (2021). The analysis involved six stages: familiarization with the data, generation of initial codes, categorization of related codes, theme development, theme review and refinement, and thematic interpretation. All interview transcripts, observation records, and documentary evidence were systematically coded and organized using NVivo 14 software to facilitate data management, coding procedures, and visualization of relationships among themes.

To ensure trustworthiness, the study adopted the criteria proposed by Lincoln and Guba (1985),

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JURAGAN
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including credibility, transferability, dependability, and confirmability . Credibility was established through source triangulation and methodological triangulation by comparing information obtained from students, teachers, and documentary evidence across observation, interview, and document analysis techniques. Member checking was also conducted by allowing participants to review summaries of interview findings. Transferability was enhanced through detailed descriptions of the research context, participants, and learning environment. Dependability was maintained through an audit trail documenting all stages of the research process, while confirmability was ensured through researcher reflexivity and systematic documentation of analytical decisions.

Ethical considerations were observed throughout the study. Permission to conduct the research was obtained from the school administration, and informed consent was secured from parents or guardians prior to data collection. Participants were informed about the purpose of the study, research procedures, voluntary participation, confidentiality measures, and their right to withdraw at any stage of the research process. To protect privacy, all participant identities were anonymized using pseudonyms, and all research data were securely stored and used exclusively for academic purposes.

RESULTS AND DISCUSSION

The findings of this qualitative phenomenography demonstrate that the formation of conceptual understanding in Science and Social Studies (IPAS), specifically regarding the solar system topic, is a non-linear process mediated through a digital exploration space. Data gathered from participant observations, in-depth interviews, and document analysis revealed that students do not merely absorb digital information passively. Instead, they actively construct psychological representations and conceptual meanings through four interconnected empirical dynamics.

Theme 1. Digital Visualization Transforms Memorization into Conceptual Understanding

The first finding reveals that digital exploration spaces transformed students' learning from simple memorization toward conceptual understanding through visualization. Interview data indicated that students perceived digital media as providing richer and more meaningful representations of solar system concepts than traditional textbook images.

Student S-1 explained: *"I love it so much, Teacher, because books usually only have static images. When we went around the planets digitally yesterday, it showed the planets actually spinning with real animations."* (Interview, February 18, 2026).

Similarly, Student S-3 reported:
"Usually, we are just asked to memorize the names—Mercury, Venus, Earth, Mars. Now I know what they actually look like." (Interview, February 18, 2026).

A deeper conceptual shift was evident in Student S-2's explanation:
"When I watched the 3D simulation yesterday, I finally saw that rotation means the Earth spins on its own axis like a toy top, while revolution means the Earth moves around the Sun." (Interview, February 18, 2026).

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JURAGAN
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These findings suggest that visualization functions as a cognitive bridge between abstract astronomical concepts and students' mental representations. Prior to the intervention, students primarily demonstrated factual recall of planetary names and characteristics. However, exposure to animated simulations and three-dimensional models enabled them to distinguish scientific concepts such as rotation and revolution, indicating movement toward deeper conceptual understanding.

This finding supports constructivist learning theory, which argues that conceptual knowledge develops when learners actively construct meaning from experiences. The result is also consistent with previous studies demonstrating that digital visualization enhances understanding of scientific phenomena that cannot be directly observed (Sinatra & Lombardi, 2023). In the context of solar system learning, visualization effectively reduced cognitive abstraction and facilitated active conceptual reconstruction.

Theme 2. Digital Exploration Encourages Active Meaning-Making

The second finding demonstrates that conceptual understanding emerged through active exploration rather than passive reception of information. Students were not merely consuming information but actively engaging with digital resources, questioning ideas, and comparing information obtained from various sources. Evidence of active meaning-making was reflected in students' responses and supported by the teacher's observations.

The teacher explained:
"I designed the digital exploration space by integrating QR codes, orbital movement simulation videos, and three-dimensional models. The main goal is for this technology to serve as a socio-cognitive space for children to construct their own understanding from abstract notions into concrete mental representations." (Teacher Interview, February 18, 2026).

The process of active exploration enabled students to move beyond remembering isolated facts toward establishing relationships among concepts. Nevertheless, the findings also revealed cognitive challenges during exploration.

Student S-5 stated:
"When we were asked to connect the planet size data with their distances in the interactive video, I got a bit confused. There was too much information on the screen." (Interview, February 18, 2026).

This response indicates that while digital exploration promotes inquiry and independent learning, excessive information may generate cognitive load that affects students' ability to process and integrate concepts effectively. Therefore, the effectiveness of digital exploration depends not only on technological features but also on instructional design that guides learners' attention toward essential conceptual relationships (Bond et al., 2024). From the perspective of Understanding by Design (UbD), these findings demonstrate that meaningful understanding

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JURAGAN
JURNAL RAGAM PENGABDIAN - PENELITIAN

develops when students engage in inquiry, exploration, and interpretation rather than merely receiving information. Digital exploration thus serves as a mechanism for fostering enduring understanding.

Theme 3. Social Interaction Facilitates Conceptual Negotiation

The third finding highlights the importance of social interaction in conceptual understanding formation. The digital exploration space functioned not only as a technological environment but also as a social environment where students negotiated meanings through collaborative discussions.

Student S-4 explained:
"Yesterday, I had a debate with my friend. He said all planets are hot because they are close to the Sun, but on the digital table, it showed that some planets are incredibly cold, like Neptune. In the end, we searched it out together using the simulation to find out why it was like that." (Interview, February 18, 2026).

This statement illustrates how conceptual conflict stimulated collaborative inquiry and promoted deeper understanding. Through discussion, students compared ideas, challenged misconceptions, and reconstructed scientific explanations.

Student S-6 further emphasized the social dimension of learning:
"At first, I was a bit afraid to speak up because I was scared of being wrong and laughed at. But when I saw that other friends also had different opinions when looking at the 3D models, I became brave enough to ask why Saturn has rings while Earth doesn't." (Interview, February 18, 2026).

The teacher similarly observed:
"Technology here successfully acts as a cultural tool that triggers dialogue. Students actively negotiate meaning while aligning digital information with their prior knowledge." (Teacher Interview, February 18, 2026).

These findings support sociocultural perspectives of learning, particularly Vygotsky's (1978) concept that knowledge is constructed through social interaction. The digital exploration environment provided opportunities for collaborative meaning-making, enabling students to refine and validate their understanding through peer interaction and teacher scaffolding. Interestingly, the findings also reveal an emotional dimension of learning. Students initially experienced academic anxiety and fear of making mistakes, yet collaborative exploration gradually increased their confidence to participate in discussions (Kumpulainen & Rajala, 2022). This suggests that conceptual understanding is influenced not only by cognitive processes but also by affective experiences during learning.

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JURAGAN
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Theme 4. Reflection Promotes Deeper Conceptual Understanding

The final finding indicates that reflection played a crucial role in developing deeper conceptual understanding. Evidence from interviews suggests that students progressed from isolated factual knowledge toward relational understanding of scientific phenomena.

Student S-7 explained:
"I just realized that all celestial bodies are interconnected because of gravity. So, planets don't collide because their paths fit perfectly in their respective orbits." (Interview, February 18, 2026).

This response demonstrates relational thinking because the student connected multiple concepts, including gravity, orbital movement, and planetary interactions, into a coherent explanation. Such understanding extends beyond memorization and reflects conceptual integration.

The teacher further noted:
"In the beginning, the children were at the unistructural or multistructural level; they only memorized isolated names or characteristics. However, after interacting with the digital simulations and discussing, they began to enter the relational level." (Teacher Interview, February 18, 2026).

The emergence of higher-order questioning also reflected deeper conceptual engagement. Student S-9 asked:
"What if the Sun suddenly died or its gravity disappeared? Atlantic forces aside, would our Earth immediately get thrown far away into outer space?" (Interview, February 18, 2026).

This question demonstrates hypothetical reasoning and conceptual transfer beyond the immediate learning content. According to the SOLO Taxonomy, such responses indicate movement toward higher levels of cognitive complexity, where learners begin extending concepts to unfamiliar situations (Utami & Kusuma, 2024). Within the UbD framework (Wiggins & McTighe, 2022), reflection serves as an essential mechanism for developing enduring understanding. Students not only acquired information about the solar system but also used that knowledge to interpret broader scientific possibilities and relationships.

Synthesis of Findings

The findings indicate that conceptual understanding in elementary IPAS learning emerged through four interconnected mechanisms: visualization, exploration, social interaction, and reflection. Digital visualization reduced conceptual abstraction, exploration encouraged active meaning-making, social interaction facilitated conceptual negotiation, and reflection supported conceptual integration. Together, these processes enabled students to progress from factual recall toward relational understanding of solar system concepts.

The study contributes to existing literature by demonstrating that digital exploration spaces do not merely improve learning outcomes but shape the processes through which conceptual understanding is formed. The findings suggest that meaningful science learning occurs when technological affordances are combined with opportunities for exploration, collaboration, and reflection. Consequently, the design of digital learning environments should prioritize conceptual engagement rather than information delivery alone.

Proposed Conceptual Model of Conceptual Understanding Formation

Based on the thematic findings, this study proposes that conceptual understanding in elementary IPAS learning is formed through a four-stage process consisting of digital visualization, active exploration, social negotiation, and reflective integration.

The process begins with digital visualization, which helps students transform abstract scientific phenomena into concrete mental representations. Through active exploration of digital resources, students construct meaning by connecting new information with prior knowledge. Social negotiation subsequently occurs through collaborative discussions and peer interactions, enabling students to clarify misconceptions and refine conceptual understanding. Finally, reflective integration allows students to connect multiple concepts into coherent scientific explanations and transfer their understanding to new situations. This model extends previous studies that primarily examined the effectiveness of digital media by explaining the mechanisms through which conceptual understanding develops in technology-enhanced learning environments.

Based on the thematic analysis, this study proposes a conceptual model explaining how conceptual understanding develops within a digital exploration environment. The model demonstrates that students' conceptual understanding is not formed solely through exposure to digital content, but through a sequence of interconnected processes involving visualization, exploration, social negotiation, and reflection. The proposed model is presented in Figure 2.

Figure 2. Conceptual Understanding Formation Model in Digital Exploration Space

The model illustrates the process through which elementary students develop conceptual understanding during digital solar system learning. Conceptual understanding emerges through four interconnected stages: digital visualization, active exploration, social negotiation, and reflective integration. These processes collectively facilitate the transition from factual recall to deeper conceptual understanding.

Figure 2 shows that digital visualization serves as the initial mechanism for transforming abstract astronomical phenomena into concrete mental representations. Through active exploration, students engage with digital resources and construct meaning from the information encountered. Social negotiation then occurs through collaborative discussions and peer interactions that help clarify misconceptions and strengthen understanding. Finally, reflective

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JURAGAN
JURNAL RAGAM PENGABDIAN - PENELITIAN

integration enables students to connect multiple concepts into coherent scientific explanations, resulting in deeper conceptual understanding of the solar system.

Theoretical and Practical Contributions

Theoretical Contributions

This study extends existing research on digital learning by demonstrating that digital exploration spaces function not merely as information delivery tools but as socio-cognitive environments in which conceptual understanding is actively constructed. The findings contribute to constructivist and sociocultural perspectives by explaining how visualization, exploration, interaction, and reflection collectively support conceptual learning.

The study also enriches the Understanding by Design framework by illustrating how digital exploration activities facilitate enduring understanding. Furthermore, the findings support SOLO Taxonomy by demonstrating students' progression from multistructural understanding toward relational understanding.

Practical Contributions

Practically, the findings suggest that teachers should design digital learning environments that encourage exploration, collaboration, and reflection rather than relying solely on technology for information presentation. Digital tools become educationally meaningful when they support students in visualizing abstract concepts, discussing ideas with peers, and reflecting on their learning experiences.

Consequently, elementary science instruction should prioritize the creation of exploration-rich learning environments that enable students to construct knowledge actively and develop deeper conceptual understanding beyond memorization.

CONCLUSION

This study aimed to explore how a digital exploration space shapes elementary students' conceptual understanding of the solar system in IPAS learning. The findings indicate that conceptual understanding is formed through a sequential process involving digital visualization, active exploration, social negotiation, and reflective integration. Through these interconnected processes, students progressed from factual memorization toward deeper conceptual understanding by connecting, interpreting, and applying scientific concepts.

The study reveals that digital exploration spaces function not merely as technological tools for information delivery but as socio-cognitive learning environments that support knowledge construction. Digital visualization helped students transform abstract astronomical phenomena into concrete mental representations, active exploration encouraged meaning-making, social interaction facilitated conceptual negotiation, and reflection enabled students to integrate concepts into coherent scientific explanations.

The main scientific contribution of this study is the proposed conceptual model demonstrating that conceptual understanding in elementary IPAS learning develops through four interconnected stages: digital visualization, active exploration, social negotiation, and reflective integration. This finding extends the application of Understanding by Design (UbD), SOLO Taxonomy, and social constructivist perspectives by explaining the mechanisms through which conceptual understanding is developed within digital learning

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JURAGAN
JURNAL RAGAM PENGABDIAN - PENELITIAN

environments.

Although the study provides valuable insights, it was conducted within a single elementary school context and involved a limited number of participants. Future research is therefore recommended to examine the proposed conceptual model across different educational settings and learning topics, as well as to investigate the long-term development of conceptual understanding through digital exploration using qualitative, quantitative, or mixed-methods approaches.

Recommendation

Based on the findings of this study, several recommendations can be proposed. First, elementary school teachers are encouraged to design IPAS learning environments that integrate digital exploration activities with opportunities for discussion and reflection. The findings indicate that conceptual understanding develops not only through exposure to digital information but also through active meaning-making, social interaction, and reflective thinking.

Second, curriculum developers should consider incorporating digital exploration spaces into science learning designs, particularly for abstract topics such as the solar system. Learning activities should be structured to support visualization, inquiry, collaboration, and conceptual integration rather than focusing solely on content delivery.

Third, school administrators and educational policymakers are encouraged to strengthen digital learning ecosystems by providing not only technological infrastructure but also professional development programs that enhance teachers' pedagogical competencies in technology-enhanced learning.

Several limitations should also be considered. This study was conducted in a single elementary school context with a limited number of participants, which may influence the transferability of the findings. In addition, the relatively short observation period did not allow the researcher to examine the long-term sustainability of students' conceptual understanding. Future studies are therefore recommended to investigate similar phenomena across diverse educational settings and subject areas, as well as to examine longitudinal changes in conceptual understanding through digital exploration environments.

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