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Research Article

Misconceptions in Planetary Geography: A Formative Expert Evaluation of a Serious Game Integrating Augmented Reality and Artificial Intelligence

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Abstract: Geography education increasingly requires planetary-scale reasoning but teachers often lack tools to make abstract concepts—such as the greenhouse effect—accessible to young learners. This study evaluates *Academia of ARistarchus*, an artificial intelligence/augmented reality (AR) hybrid serious game developed through design-based research (DBR) that positions planetary geography as a pedagogical lens. By extending core geographical concepts into planetary contexts, the tool helps students understand Earth as a complex system. A purposive panel of six experts evaluated the prototype through a structured walkthrough informed by adapted game user experience satisfaction scale and handheld augmented reality usability scale, semi-structured interviews, and a targeted review of documented misconceptions. Initial quantitative feedback using a 5-point Likert instrument showed consistent agreement (above 4.0) across engagement, usability, and perceived learning value. Qualitative findings indicated that comparative planetology—contrasting Earth, Venus, and Mars—makes the greenhouse effect more tangible, while AR visualisations address key challenges related to scale. The rule-based feedback agent, *Aristarchus*, further supports conceptual change by diagnosing misconceptions. Expert feedback led to concrete refinements, including improved instructional videos. Overall, the study proposes a transferable model for scaffolding macroscale spatial reasoning and operationalising comparative analysis as a mode of geographical inquiry. Rather than claiming definitive effectiveness, this formative evaluation demonstrates how DBR-driven expert review can systematically inform design prior to classroom implementation, offering a replicable protocol for technology-enhanced geography interventions.

Keywords: planetary geography; serious games; augmented reality (AR); design-based research (DBR); geographical misconceptions; expert evaluation

Highlights:

- Conceptualises planetary geography as a lens for comparative atmospheric studies.
- Implements a hybrid DBR model integrating AR visuals and a tutoring agent.
- Provides a validated protocol for scaffolding macroscale spatial reasoning.

1. Introduction

To understand Earth in the twenty-first century, it is essential to view it within a wider planetary context. Comparative studies of the Solar System show that key terrestrial processes—such as atmospheric evolution and the conditions that make a planet habitable—have clear analogues on neighbouring planets. The runaway greenhouse effect on Venus and the thin, cold atmosphere of Mars provide natural laboratories for exploring Earth's climate system and its limits (Haberle, 2013; Baines et al. 2015). Although upper primary learners (ages 10–12) are developmentally ready to reason about systems, scale remains a major challenge (Skarstein & Wolff, 2020). Comparative examples offer a concrete entry point to otherwise abstract planetary processes. Geography curricula emphasise systems thinking, spatial literacy, and sustainability—competences that rely on a students' ability to reason across scales (Lambert & Morgan, 2010). Recent research in geography education highlights the importance of designing learning experiences that enhance student motivation and engagement (Fraile-Jurado & Periáñez-Cuevas, 2023). Effective tools for teaching these large-scale concepts, particularly through augmented reality (AR), remain limited. As a result, traditional methods often fail to address persistent misconceptions (Gautier et al., 2006; Shepardson et al., 2011).

To address this gap, we introduce *Academla of ARistarchus*, a hybrid serious game that combines a physical board-game, AR visualisations, and a rule-based intelligent tutor agent. Designed for learners aged 10–12, the game promotes planetary geographical thinking by enabling comparative study of planetary atmospheres (Earth, Venus, and Mars). It also supports large-scale spatial reasoning and offers adaptive feedback to help students revise their mental models and overcome misconceptions.

This study reports on a formative expert evaluation of the prototype, conducted as Phase 2 of a design-based research (DBR) cycle (McKenney & Reeves, 2018; Wang & Hannafin, 2005). Our aims were to set out the theoretical foundation of the design and to examine its pedagogical, technological, and scientific coherence through expert review. At this stage, we did not assess learning outcomes; instead, we focused on design readiness for classroom implementation. Expert feedback suggests that the integration of AR with the intelligent tutor provides a coherent framework for addressing abstract concepts, although further empirical testing is needed to determine its impact on student learning.

The study is guided by two research questions (RQs):

- **RQ 1 (pedagogical and disciplinary coherence):** How do experts evaluate the game's alignment with planetary geography education goals?
 - RQ 1.1: To what extent does the game encourage comparative, multiscale thinking about planetary atmospheres?
 - RQ 1.2: To what extent does the game address documented geographical misconceptions?
- **RQ 2 (technological and instructional integration):** How do experts evaluate the integration of AR and the rule-based intelligent tutor agent?
 - RQ 2.1: What is the perceived usability and educational value of AR visualisations?
 - RQ 2.2: How effectively does the feedback agent support instructional flow?

According to Bampasidis et al. (2025), few pedagogical frameworks integrate planetary thinking with transitions between spatial scales, and even fewer combine these with AR-supported serious gameplay. This represents a clear gap in geography education. Multiscale and comparative thinking are recognised as essential skills for learners aged 10–12, who often have difficulties understanding planetary-scale phenomena (Lambert & Morgan, 2010; Skarstein & Wolff, 2020). These spatial abilities develop from early childhood and underpin later geographical reasoning (Zisi & Klonari, 2022). We need to address geographical misconceptions—such as confusion between the greenhouse effect and ozone depletion—because this is crucial for helping students revise their mental models (Gautier et al., 2006; Shepardson et al., 2011). Previous studies show that AR and AI can enhance spatial and systems thinking, when clearly aligned with instructional goals (Carbonell & Bermejo, 2017; Mishra & Koehler, 2006). AR makes large-scale atmospheric structures more tangible, while an intelligent tutor can provide adaptive feedback that directly addresses misconceptions capabilities that traditional resources cannot offer.

2. Literature Review and Theoretical Framework

Our study is structured around three interconnected layers. Planetary geography forms the disciplinary core, defining the knowledge students are expected to develop. Documented geographical misconceptions clarified the pedagogical problem our tool seeks to address and shaped the design of its feedback logic. To ensure that technological decisions were pedagogically and disciplinarily aligned, we adopted the Technological Pedagogical Content Knowledge

(TPACK) framework (Mishra & Koehler, 2006). Additional principles were used in a supplementary way but remained secondary to the core framework.

2.1. Planetary Geography: A Disciplinary Lens for Multiscale, Comparative Thinking

In this study, we define planetary geography as a pedagogical lens that applies core geographical concepts—space, place, scale, comparison, and human–environment interaction— (Chang & Kidman, 2021) beyond an Earth-centred perspective. We adapt these concepts to other planetary bodies, treating them as analytically comparable spatial systems. Instead of redefining geography as an astronomical discipline, we conceptualise planetary geography as a structured comparative approach: planets are distinct but systematically comparable places. This perspective enables learners to examine how similar physical processes operating under different boundary conditions produce environmental outcomes. Through multiscale reasoning and cross-planetary comparison, we reinforce geographical inquiry by situating Earth within a broader planetary context.

Geography education needs to address phenomena that transcend national borders and planetary boundaries (Larsen et al., 2022). In response, we use planetary geography to analyse planetary bodies as an arena of spatial organisation (Lambert & Morgan, 2010). This approach reflects emerging planetary pedagogies (Kidman & Chang, 2025). It situates Earth within broader ecological systems and enables learners to apply familiar reasoning practices—comparison, scale analysis, and systems thinking—within a planetary setting.

The pedagogical value of this lens lies in how it uses scale as a structuring concept (Skarstein & Wolff, 2020). Learners are required to shift their focus between local, global, and planetary levels of analysis—a core geographical competence that remains undertaught in school curricula (Lambert & Morgan, 2010; Skarstein & Wolff, 2020). By presenting Earth, Venus, and Mars as analytically distinct places with their own atmospheric histories, our framework turns abstract ideas—such as the greenhouse effect—into concrete objects of comparison. The runaway greenhouse effect on Venus and the thin atmosphere of Mars act as extreme cases against which to understand Earth’s climate system not as unique but as part of a continuum of planetary evolution. Bringing planetary geography into the classroom becomes an exercise in reasoning across very large spatial scales. It requires students to navigate distances and systems far beyond their daily experience.

While planetary atmospheres and the greenhouse effect are also central topics in physics and Earth science education, the approach we adopt in this study differs in its epistemological focus. Physics typically emphasises the quantitative modelling of radiative processes and atmospheric mechanisms, whereas Earth science often centres on system dynamics and empirical environmental observation. On the other hand, planetary geography frames these phenomena as spatially situated and comparatively constructed objects of geographical inquiry. Instead of replacing disciplinary content from physics, this approach situates atmospheric processes through spatial comparison, scale transitions, and human–environment interpretation (Chang & Kidman, 2021). Treating Earth, Venus, and Mars as analytically comparable places shifts the emphasis from explaining physical laws alone to understanding how identical physical principles produce divergent environmental outcomes under different boundary conditions. Planetary geography thus complements, rather than competes with science-based instruction.

Our framing operationalises three core geographical capabilities often undertaught in upper primary curricula:

- **Multiscale reasoning:** The narrative progression of the game—from Samos to Earth, and then to Mars and Venus—facilitates learners in shifting between local, global, and planetary scales—a key source of student difficulty (Lambert & Morgan, 2010; Skarstein & Wolff, 2020). This shift supports human–environment thinking by helping students recognise how local actions accumulate into planetary-scale impacts (Larsen et al., 2022).
- **Comparative methodology:** We treat Earth, Venus, and Mars not as astronomical objects but as analytical places whose atmospheric histories we systematically compare. This approach embodies the geographical question, “*Why is it different here from there?*” and shows how physical principles can lead to different environments under varying boundary conditions.
- **Planetary sense of place:** The narrative presents each planet as a distinct place with its own environmental trajectory, extending place-based pedagogy beyond Earth. Huckle and Wals (2015) emphasis on global responsibility, sustainability, and the interconnectedness of socio-ecological systems aligns closely with this broader pedagogical perspective. This extension supports our goal of preparing students to navigate the challenges of the Anthropocene by viewing Earth as a fragile, interconnected system (Larsen et al., 2022).

Building on this, we conceptualised the discipline within the powerful knowledge framework (Maude, 2016; Young, 2008). This framework argues that geography education should provide students with specialised conceptual tools to understand the world in ways that go beyond everyday experience. By extending core concepts—such as scale and comparison—to planetary contexts, our design offers what Maude (2016) identifies as a key pillar of geographical knowledge: the ability to perceive Earth as a complex, interconnected system.

2.2. *The Pedagogical Challenge: Geographical Misconceptions as Barriers to Planetary Thinking*

In an era of algorithmic misinformation, promoting planetary-scale thinking through hybrid tools (AR/AI) also develops critical geoliteracy, enabling students to ethically interpret complex spatial data about the changing world (Kidman & Chang, 2025). While planetary geography defines what students need to learn, the rationale for our approach is rooted in a well-documented pedagogical obstacle: persistent misconceptions that act as a barrier to students' understanding of atmospheric and climate systems (Reinfried, 2006; Vosniadou, 2008). In geography education, such misconceptions are not knowledge gaps—they constitute effective alternative mental models that filter new information and resist traditional instruction (Özdemir & Clark, 2007).

A particularly persistent example is the misunderstanding of the greenhouse effect as ozone layer depletion. This misunderstanding fundamentally misrepresents climate change mechanisms and remains common even after instruction (Gautier et al., 2006; Shepardson et al., 2011). These misconceptions are geographical: they involve misunderstandings of spatial relationships (e.g., the vertical structure of the atmosphere), of scale (e.g., the difference between local pollution and global radiative forcing), and of systemic interconnections.

In this study, we treat conceptual change theory (Vosniadou, 2008) not as an independent pedagogical framework but as the theoretical specification of the problem our intervention aims to address. Documented misconceptions directly informed the rule-based logic of the feedback agent, Aristarchus. We designed its graduated feedback protocol—Hint, then Targeted Feedback, then Full Explanation—to implement cognitive conflict and supporting strategies known to facilitate conceptual restructuring (Chang et al., 2018). Conceptual change thus functions as the pedagogical engine driving the intelligent component, ensuring that technology serves a clearly defined geographical learning goal. The AI's conversational protocol delivers concise, focused feedback, while the AR interface emphasises clarity by presenting key concepts without irrelevant information. Experts positively highlighted these design choices—which are connected with cognitive load theory (Sweller, 2011)—during the evaluation, particularly regarding AR comprehensibility and the AI's supportive role.

2.3. *Designing for Planetary Geography: TPACK as an Integrative Tool*

Translating planetary geography and conceptual change principles into a functioning hybrid learning environment requires a systematic design approach. In this study, we employ the TPACK framework (Mishra & Koehler, 2006) not only as an analytical lens but as a generative design tool to ensure that technological decisions are pedagogically and disciplinarily connected. Within this application:

- **Content knowledge (CK):** We define it exclusively through planetary geography—the comparative study of atmospheric composition, structure, and climate outcomes across Earth, Venus, and Mars as distinct spatial systems (as defined in Section 2.1).
- **Pedagogical knowledge (PK):** We shape it around the need to promote conceptual change through inquiry-based collaboration, structured comparative analysis, and targeted misconception diagnosis.
- **Technological knowledge (TK):** It comprises AR for spatial visualisation of planetary atmospheres and a rule-based intelligent tutoring agent, Aristarchus, for adaptive feedback.

We use TPACK (Mishra & Koehler, 2006) as a disciplining device: it ensures that we include technology only when justified by the intersection of content, pedagogical, and technological knowledge. The AR component is not a general-purpose visualisation tool. Instead, we designed it specifically to render macroscale atmospheric structures manipulable, directly supporting the comparative geographical reasoning defined by our content knowledge. Similarly, the Aristarchus is not a generic chatbot. We hard-coded its logic to diagnose the precise geographical misconceptions documented in Section 2.2, and we calibrated its scaffolding to the conceptual change strategies appropriate for the content. TPACK thus provides the “*how*” that links the disciplinary “*what*” (planetary geography) with the pedagogical “*why*” (conceptual change).

3. The Academla of ARistarchus: Design Rationale

3.1. Core Pedagogical Logic

Academla of ARistarchus is a hybrid serious game designed for learners aged 10–12. It integrates physical board-game components with digital AR visualisations and a rule-based intelligent tutoring agent, Aristarchus. The game’s pedagogical logic is based on three interconnected pillars derived from the theoretical framework:

- **Comparative planetary analysis** renders abstract atmospheric processes tangible by providing extreme cases—Venus and Mars—against which students can systematically compare Earth’s climate system.
- **Manipulable, macroscale spatial representations** address the pedagogical challenge of scale by allowing learners to physically explore three-dimensional atmospheric structures that cannot be directly observed or experienced.
- **Misconception-targeted, adaptive feedback** identifies and helps to restructure entrenched alternative mental models by creating gradual cognitive conflict and providing clear explanations.
- **Collaborative gameplay** supports groups of three players, with a Research Director managing procedural tasks.

3.2. Game Components and Functions

Table 1 presents the five interconnected components of the prototype, each serving a defined pedagogical function aligned with the study’s research questions. A detailed, interactive presentation of the game—including its narrative, rules, and components—is available at <https://arcg.is/OLSfuD1>.

Table 1. Game Components, Pedagogical Function, and Design Rationale

Component	Description	Pedagogical function	TPACK justification	RQ alignment
Quiz Cards	Progressively scaffolded questions (recall → analysis)	Formative assessment; conceptual understanding	PK: scaffolded questioning; CK: planetary atmosphere content	RQ1.1
Challenge Cards	Collaborative missions requiring synthesis of AR, board, and agent information	Promotion of spatial reasoning, communication, and teamwork	PK: collaborative inquiry; CK: multiscale geographical reasoning	RQ1.1, RQ2.2
AR Squares	Interactive 3D models of Earth, Venus, and Mars	<i>Operationalise abstract atmospheric structures as manipulable objects</i> ; develop macroscale spatial literacy	TK: AR visualisation; PK: spatial manipulability; CK: atmospheric structure and scale	RQ2.1
Feedback Agent (Aristarchus)	Rule-based intelligent tutoring system; graduated feedback (Hint → Targeted → Full)	Diagnose 10 documented misconceptions; provide adaptive scaffolding	TK: rule-based AI; PK: conceptual change strategies; CK: misconception-specific content	RQ1.2, RQ2.2
pAsspoRt System	Physical passport: AR interaction unlocks pro-environment stickers	Link scientific understanding to ethical agency; support tangible sustainability actions	PK: ethical reflection; CK: human–environment interaction	RQ1.1

3.3. Feedback Agent: A Rule-Based System for Misconception Diagnosis

Aristarchus, the agent, is programmed to diagnose and help learners work through ten persistent geographical misconceptions. These were drawn directly from the literature on planetary atmospheres (Baines et al., 2015), and the greenhouse effect (Gautier et al., 2006; Shepardson et al., 2011).

The agent employs a graduated feedback protocol:

- **Hint (first response):** A brief, analogy-based cue that prompts learners to reconsider their reasoning.
- **Targeted Feedback (if the misconception persists):** An explicit explanation that addresses the specific misunderstanding.
- **Full Explanation (after repeated errors or upon request):** A comprehensive conceptual clarification.

We designed all feedback scripts to be age-appropriate for learners aged 10–12, using analogies and everyday language while maintaining scientific accuracy (see an example in Appendix A).

3.4. AR for Macroscale Spatial Reasoning

The AR component renders three-dimensional, data-driven models of Earth, Venus, and Mars based on ESA and NASA mission data. Learners can move physically around the models, zoom in, and compare atmospheric layers across the three planets. This functionality directly addresses the pedagogical challenge identified in Section 2.2—the difficulty of comprehending atmospheric scale and structure through static, two-dimensional diagrams. The AR component is not a separate application; it is triggered by, and feeds back into, the board-game mechanics. Successful AR interactions unlock pAsspoRt stickers and provide data required for Challenge Card missions, ensuring the technology is integrally embedded within the gameplay rather than serving as decorative or isolated functionality.

3.5. Narrative and Place-Making

The game world is set in Samos, Greece—the birthplace of the ancient astronomer Aristarchus. Players adopt the role of geographer–scientists and embark on a multiscale journey from the local (Samos) to the global (Earth) and finally to the planetary (Venus and Mars). We designed this narrative structure to intentionally scaffold the cognitive shift between spatial scales and to frame each planet as a distinct place with its own environmental history, operationalising the concept of sense of place in a non-terrestrial context (Larsen & Harrington, 2018; Semken et al., 2017).

The pAsspoRt system translates scientific understanding into personal consideration. We further enhanced the game by Crisis Scenario Cards, introduced following expert feedback (see Section 5.3, Table 4). These cards present short dilemmas that require groups to apply their scientific knowledge to realistic mitigation actions (e.g., cycling, planting trees, and reducing food waste).

The spatial progression of the Earth-level board visually represents this story progression, guiding students through geographically distributed challenge nodes and AR activation points that structure the learning sequence.

4. Methodology: A Design-Based Expert Evaluation Study

4.1. Research Design and Positioning

Following DBR methodology (McKenney & Reeves, 2018) in geography education, our study treats expert evaluation as a key formative phase before classroom implementation. In doing so, it contributes to the broader body of design knowledge in the field. This paper reports on the formative expert evaluation phase (Phase 2) of a broader DBR cycle (Wang & Hannafin, 2005). Building on the theoretical and conceptual design outlined in Section 2 and the prototype development described in Section 3, this phase examines whether the *Academia of ARistarchus* prototype is pedagogically valid, scientifically accurate, and technologically reliable before it is used in classroom testing.

Expert evaluation at this stage helps improve the intervention through structured feedback, following the iterative phases of DBR (McKenney & Reeves, 2018). Our study focuses on design quality, usability, and perceived potential—all preliminary steps for any subsequent investigation of learning outcomes.

4.2. Participants: The Expert Panel

A purposive sampling strategy was used to recruit a multidisciplinary panel of six experts. This sample size is methodologically appropriate for formative expert evaluation in early-stage DBR. The aim is to reach theoretical saturation of critical feedback and ensure a range of perspectives instead of achieving statistical generalisability (McKenney &

Reeves, 2018). We selected each expert to represent a distinct, non-overlapping dimension of the hybrid innovation. We identified potential experts through our professional networks and a review of recent publications in the relevant fields; they were invited based on their demonstrated expertise aligning with the specific evaluation focuses outlined in Table 2.

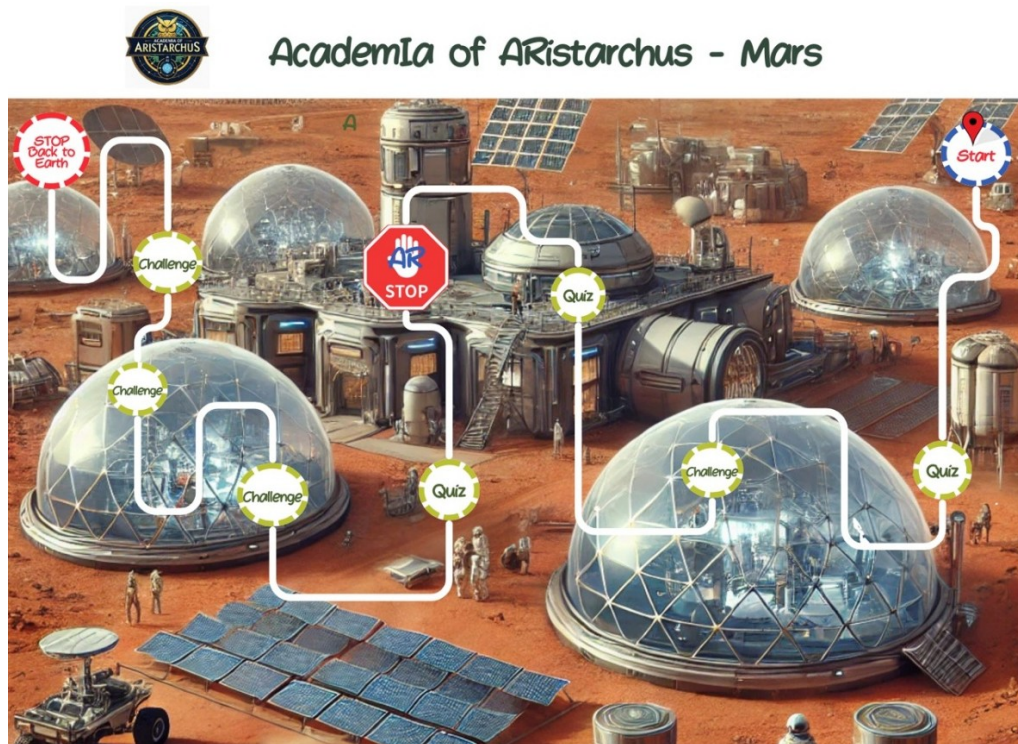


Figure 1. Mars-Level Gameplay Board Illustrating the Spatial Progression and Challenge Nodes Within the Planetary Geography Framework



Figure 2. AR Earth Visualisation Activated Through a Game Marker, Enabling 3D Interaction With Planetary Systems

An essential inclusion criterion was direct teaching or design experience relevant to the target age group (10–12 years). We selected the six experts based on predefined criteria: (a) a doctoral degree or equivalent expertise in geography education, STEM education, educational technology, or climate science; (b) a minimum of five years of professional or research experience in curriculum design or digital learning environments; and (c) previous publications or project involvement related to spatial thinking, AR integration, or environmental education. Table 2 lists the six experts, their fields and the aspects focused on during the evaluation.

Table 2. Composition and Focus of the Expert Evaluation Panel

Expert ID	Field of expertise	Key evaluation focus
E1	Geography education	Curricular alignment; spatial scale; geographical concepts; scientific accuracy of geographical content
E2	Planetary science	Scientific accuracy of planetary data; age-appropriate conceptual clarity
E3	Educational technology	AR usability; technological interface; interactive features
E4	Instructional design (AI systems)	AI tutor’s adaptive scaffolding; pedagogical logic of feedback
E5	Special needs education	Inclusive pedagogy; accessibility; learner engagement strategies
E6	Primary education	Age-appropriateness; classroom feasibility; pedagogical effectiveness of content

All participants were fully informed about the purpose of the study, and they provided informed consent before their participation.

4.3. Evaluation Procedure

The evaluation was conducted through a structured expert walkthrough session. Each expert was first briefed on the game’s learning objectives and theoretical foundations—planetary geography, conceptual change, and TPACK (Mishra & Koehler, 2006)—via a standardised presentation. Experts then engaged in a practical session with the full prototype, including the physical board-game components, a functional digital simulation of the AR and feedback modules, and all narrative and game elements (Quiz Cards, Challenge Cards, AR Squares, and the pAsspoRt system).

We asked experts to interact with the prototype both as players and as observers. They were advised to focus on their specific evaluation criteria while also considering the overall learning experience. Immediately after the walkthrough, they completed the evaluation instruments and took part in a semi-structured interview, where we captured detailed qualitative feedback.

4.4. Expert Review Instrument and Data Collection Procedure

A purpose-built expert review approach was implemented to support the formative evaluation of the hybrid *Academla of ARistarchus* learning environment. Instead of relying on pre-existing full-scale instruments, we designed a custom questionnaire and follow-up interviews to collect expert perspectives on engagement, usability, pedagogical alignment, scientific accuracy, ethical considerations and instructional coherence. Since this phase of DBR cycle (McKenney & Reeves, 2018) is iterative and design-focused, this approach allows us to use what we learn to guide our next steps.

For this formative DBR phase, a purpose-built expert review questionnaire was developed with sixteen items. The items drew on core concepts of playability and usability from established tools—notably the game user experience satisfaction scale (GUESS), which focuses on engagement and playability (Phan et al., 2016) and the handheld augmented reality usability scale (HARUS), which emphasises comprehensibility and manipulability of AR interfaces (Ibáñez & Delgado-Kloos, 2018), as well as contemporary heuristic evaluation approaches for games (Iyer et al., 2025). We did not

apply the original validated scales in full, nor did we replicate them psychometrically. Instead, we adapted relevant constructs to fit the hybrid nature of the tool—combining a board-game, AR, and AI-supported guidance.

The resulting instrument was organised into five thematic areas, each reflecting a different aspect of the hybrid design: user experience and engagement, AR usability, pedagogical alignment, scientific accuracy, and instructional coherence. For analysis and presentation, we grouped these five areas into four broader evaluation dimensions. We did this based on conceptual overlap and to keep the reporting of formative feedback concise. The results (Section 5.1, Table 3) are presented under four consolidated dimensions: pedagogical alignment and disciplinary coherence (areas 3 and 5), technological functionality and AR usability (area 2), content validity and scientific accuracy (area 4), and instructional coherence and systemic integration (areas 5 and 1). User experience and engagement (area 1) was instead analysed separately through qualitative thematic analysis (Section 5.2) to obtain more detailed feedback. This restructuring was simply to make the findings clear; it did not change how the original ratings were interpreted.

Given the small expert sample, we analysed quantitative responses descriptively (mean scores per dimension) without making claims about generalisability. We did not conduct reliability or factor analysis—at this stage, the purpose was formative design refinement, not scale validation or generalisable inference. Unequal weighting of dimensions was theoretically justified to reflect their functional roles within a hybrid technology-enhanced learning system. We complemented the questionnaire with semi-structured expert interviews and analysed the qualitative data through iterative thematic comparison across expert responses. This allowed us to triangulate and interpret the quantitative findings.

4.5. Data Analysis

Data analysis followed a parallel mixed-methods strategy to integrate findings from the purpose-built expert review instrument and follow-up interviews.

Quantitative analysis: We analysed data from the adapted GUESS and HARUS informed questionnaire using descriptive statistics (mean and standard deviation). Given the small, purposive expert sample and the formative nature of this DBR phase, we did not use statistical tests. We present the quantitative findings as indicators of perceived quality rather than definitive measures, interpreting them with appropriate caution regarding potential courtesy bias or halo effects (see Section 6.4).

Qualitative analysis: We transcribed semi-structured interviews and written misconception review comments and analysed using reflexive thematic analysis (Braun & Clarke, 2006). Our process involved familiarisation through repeated reading, systematic coding of meaning units theme development through iterative comparison and clustering theme review against coded extracts and the full dataset, and theme definition and naming. We guided the analysis by the two research questions. Two researchers coded independently and then met to compare and finalise themes through discussion. We used a hybrid coding approach, combining themes derived from the research questions and the GUESS/HARUS frameworks. The four themes we present in Section 5.2 reflect the range of expert perspectives identified during analysis. We did not apply hierarchical weighting, reflecting the formative purpose of this DBR phase.

In this formative DBR phase (McKenney & Reeves, 2018), we prioritised qualitative findings as the primary source of diagnostic insight, using quantitative ratings as contextual indicators of expert approval. This triangulated approach ensures that design refinements are grounded in detailed expert reasoning rather than summary scores alone, while still providing a broad measure of overall satisfaction.

4.6. Ethical Considerations

The study was conducted according to the ethical standards for research involving human participants. We obtained informed consent from all individual participants. All procedures performed were approved by the institutional and national research committee.

5. Results

5.1. Quantitative Findings

Table 3 presents descriptive statistics for the four evaluation dimensions derived from the structured expert review.

Table 3. Expert Evaluation Results: Quantitative Ratings by Dimension (n = 6)

Evaluation dimension	Mean (1–5)	SD
Pedagogical alignment & disciplinary coherence	4.6	0.52
Technological functionality & AR usability	4.4	0.55
Content validity & scientific accuracy	4.8	0.41
Instructional coherence & systemic integration	4.5	0.55

Ratings are based on a 5-point Likert scale (1 = Strongly Disagree, 5 = Strongly Agree). Given the formative nature of the study and the small expert sample, we interpret these values as qualitative indicators of design quality, not as statistical findings. All dimensions received mean scores between 4.4 and 4.8, with low standard deviations. The highest rating we observed was for content validity and scientific accuracy (M = 4.8, SD = 0.41), which highlights the experts’ confidence in the scientific accuracy of the planetary content and the effective targeting of documented misconceptions. We interpret these results with caution (see Section 6.4 for a full discussion of limitations).

5.2. Qualitative Findings

Through thematic analysis of semi-structured interviews and written misconception reviews, we identified four overarching themes, each directly addressing our research questions. These qualitative findings complement the quantitative metrics by providing detailed insights into the game’s alignment with the study’s objectives.

5.2.1. Theme 1: Comparative planetology as a powerful geographical scaffold (RQ1)

All six experts validated the decision to frame the greenhouse effect through comparative analysis of Earth, Venus, and Mars, identifying this as the game’s core disciplinary contribution. They emphasised that the comparative approach functions not as context but as an authentic application of geographical methodology. As one planetary science expert (E2) noted, “Using Venus and Mars as comparative extremes makes the abstract concept of the ‘greenhouse effect’ immediately tangible.” A geography education expert (E1) similarly highlighted that the design “forces students to de-centre Earth and think about process.” reinforcing geographical reasoning. Experts also understood the value of the multiscale narrative structure. Moving from Samos to Earth and then to Mars and Venus was seen as an effective scaffold for supporting learners’ transitions across spatial scales. As a primary education expert (E6) explained, “Ten-year-olds struggle to jump from their neighbourhood to the whole planet, let alone to another planet. The narrative gives them a handrail.”

5.2.2. Theme 2: Misconception-targeted feedback as a pedagogical asset (RQ1)

Experts consistently described Aristarchus’ misconception-targeted design as a key pedagogical strength. They emphasised that basing the feedback explicitly on documented misunderstandings distinguishes the system from conventional hint mechanisms. As E1 (geography education) explained, “The fact that the feedback is mapped directly to known misconceptions—like confusing ozone and greenhouse—moves it from a simple hint system to a tool for conceptual change.”

The structured misconception review further confirmed high agreement on scientific accuracy and age appropriateness. Two experts recommended adding visual analogies to complement textual hints, but no expert identified any inaccuracies or developmentally inappropriate content.

5.2.3. Theme 3: AR solves a genuine pedagogical problem, not a technological gimmick (RQ2)

Experts distinguished the AR component from superficial gamification or edutainment. They valued its ability to render invisible, macroscale phenomena spatially manipulable—directly addressing the well-documented pedagogical challenge of scale. As E1 (geography education) noted, “*The AR doesn’t feel like a gimmick. It solves a real problem in a way a textbook diagram never could. You can literally walk around Venus’s atmosphere.*”

However, two experts (E5 and E6) raised concerns about potential cognitive load. E6 (primary pedagogy) observed that the video clips, while visually engaging, were overly long and disrupted the instructional flow: “*The video clips are beautiful, but they’re long. During the walkthrough, I felt the flow pause. Shorter, thematically focused clips would work better.*”

5.2.4. Theme 4: Constructive critique and actionable refinements (RQ2)

Although experts were overall positive, they offered targeted critique that directly informed our design iterations. Highlighted uncertainty surrounding the Research Director role, noting that the player assigned to this role carried disproportionate instructional responsibility, which risked unbalancing collaboration. As E5 (special needs education) stated, “*The Research Director should be purely procedural—scorekeeping, not gatekeeping knowledge.*” Two experts also suggested that the pAsspoRt stickers, while engaging, would benefit from stronger integration with reflective discussion. As E1 (geography education) remarked, “*Collecting stickers is fun, but it needs a moment of reflection. Why is this action helpful? What difference does it make?*” Finally, E3 recommended increasing the contrast of the AR markers for classroom projection environments.

5.3. Design Iterations Undertaken

Based on expert feedback, we implemented the following improvements before classroom application. Table 4 summarises the key expert critiques alongside the corresponding design iterations.

These findings illustrate the formative purpose of expert evaluation within DBR (McKenney & Reeves, 2018): they do not certify quality but systematically inform the intervention by addressing practical, pedagogical, and technological challenges identified by experts. We integrated the completed changes into the prototype before classroom testing, while pending actions will be addressed in subsequent co-design cycles with teachers.

Table 4. Expert Feedback and Corresponding Design Iterations

Expert suggestion	Implemented action
Clarify Research Director role ambiguity	Research Director redefined as procedural facilitator (scorekeeping, turn management)
Deepen ethical engagement	Added Crisis Scenario Cards: short dilemmas requiring groups to apply scientific understanding to realistic mitigation choices (e.g., “ <i>Your community must reduce emissions by 20%. Which policy do you prioritise and why?</i> ”)
Shorten video clips to reduce cognitive load	Replaced long segments with shorter, thematically focused clips
Increase AR marker contrast	Adjusted visual assets for better projection visibility in classroom lighting conditions
Add visual analogies to feedback scripts	Earmarked for codesign with teachers in DBR Phase 3; not yet implemented

6. Discussion

6.1. Interpretation of Findings

The converging quantitative and qualitative findings indicate that the prototype operationalises its theoretical foundations in a manner consistent with the intended pedagogical design. Regarding RQ1, experts confirmed that the comparative planetary framing provides a coherent disciplinary and pedagogical structure for upper-primary learners.

The ratings for pedagogical alignment ($M = 4.6$) and the qualitative emphasis on comparison and scale suggest that planetary geography can function as a productive lens for geographical inquiry. The misconception-targeted design of Aristarchus further supports RQ1.2, with expert feedback confirming its potential to facilitate conceptual restructuring.

Regarding RQ2, experts evaluated both technological components as purposefully integrated instead of decorative. The AR environment was recognised for enabling spatial reasoning about atmospheric scale, while the rule-based tutor supported instructional flow through targeted scaffolding. These findings align with the ratings for technological functionality ($M = 4.4$) and instructional coherence ($M = 4.5$).

The refinements generated through expert review—simplification of the Research Director role, introduction of Crisis Scenario Cards, and reduction of video length—illustrate the diagnostic value of formative evaluation within DBR. These adjustments improve collaboration, enhance usability and reduce unnecessary cognitive load, strengthening the prototype's readiness for classroom implementation.

The study suggests that extending established geographical reasoning practices—comparison, scale navigation, and systems thinking—into a planetary context offers a model for supporting macroscale spatial reasoning. The formative evaluation protocol also provides a replicable approach for theory-driven design in geography education.

6.2. Contributions to Geography Education

Our study proposes three interrelated contributions to geography education. First, it offers a model for supporting macroscale spatial reasoning. School geography often privileges terrestrial, map-based tasks at local and national scales, while the cognitive act of scaling up to planetary systems remains comparatively underexplored in primary curricula. This approach demonstrates how AR can structure this scaling process by making transitions between Earth, Venus, and Mars cognitively and physically navigable. Although empirical learning outcomes remain to be tested, the study proposes a design approach that may inform future curriculum development. Second, the study operationalises comparison as a form of geographical inquiry. While, comparative planetology has been proposed as a pedagogical resource, its role within geography curricula has remained conceptual. Our study documents a concrete design that embeds systematic comparison as a concept-led inquiry structure (Lambert & Morgan, 2010).

Expert validation indicates that such comparison is feasible and rigorous for upper-primary learners, providing evidence for a strategy previously clarified more in principle than in practice. Third, the study extends place-based pedagogy to planetary contexts. Place-based education has traditionally centred on local experiential engagement (Gruenewald, 2008; Semken et al., 2017). The intervention shows that narrative framing and sense of place can be adapted to non-terrestrial contexts while maintaining disciplinary coherence. By treating each planet as an analytically distinct place with its own environmental trajectories, the design links scientific understanding to ethical reflection on anthropogenic impact. This extension offers a curriculum model for integrating sustainability and supporting emerging discussions within upper-primary geography.

6.3. Comparison With Prior Research

Our findings not only align with prior research in geography education. First, regarding comparative planetology, earlier work proposed planetary comparison as a means of enriching physical geography instruction, but this argument remained largely experiential. Our study provides a structured implementation of this idea, identifying design principles—such as narrative organisation of scale, misconception-informed feedback, and spatial manipulability—that support classroom feasibility. Second, in relation to climate misconceptions, previous interventions addressing the conflation of the greenhouse effect and ozone depletion have relied primarily on texts or direct instruction (Chang et al., 2018; Gautier et al., 2006). Embedding misconception diagnosis within an adaptive feedback system extends this literature into collaborative, game-based environments. Third, within technology in geography education, AR applications have supported local fieldwork and map visualisation (Carbonell & Bermejo, 2017). Extending AR to macroscale, non-terrestrial reasoning addresses a different pedagogical challenge—conceptualising atmospheric systems beyond daily experience—rather than introducing technology for its own sake. Finally, in place-based pedagogy, responding to calls for broader conceptions of place (Semken et al., 2017), our study demonstrates how narrative and ethical engagement can be maintained when shifting from local to planetary contexts.

6.4. Limitations and Future Research

Our study provides formative validation of the prototype; several limitations outline directions for future work. First, as an expert evaluation with six participants, the focus was on design readiness rather than learning effectiveness. The purposive sampling and potential halo effects mean that quantitative ratings should be interpreted cautiously. Subsequent DBR phases will include quasi-experimental classroom trials assessing conceptual understanding and spatial reasoning relative to traditional instruction. Second, regarding sample and generalisability, the multidisciplinary panel offered theoretical insights but does not permit statistical generalisation. Broader teacher involvement through co-design workshops will strengthen curricular adaptability. Third concerns about video length and hybrid integration highlight the need for systematic cognitive load measurement (e.g., Leppink et al., 2013) during classroom implementation. Fourth, the disciplinary positioning of planetary geography requires further empirical investigation. Future research should examine how teachers interpret and adopt this framing within their instructional practice. Finally, although expert scores were positive, they should be understood as formative indicators rather than measures of overall quality. In early-stage DBR, expert reviewers may be influenced by courtesy bias or halo effects. For this reason, qualitative insights were treated as the primary source of diagnostic information.

Planned Phase 3 trials will address these limitations through quasi-experimental implementation with pre-tests and post-tests measuring conceptual change (via a two-tier instrument targeting the ten documented misconceptions), spatial reasoning tasks, and systematic cognitive load assessment.

7. Conclusions

This study has reported on the formative expert evaluation of *Academla of ARistarchus*, a hybrid serious game designed to bridge planetary science with core geographical inquiry. Using a DBR framework, the study illustrates how planetary geography can be operationalised as a “*comparative laboratory*” for upper-primary learners. The findings suggest that when technological affordances, AR and AI-supported feedback, are connected with documented geographical misconceptions, they can move beyond surface engagement to support deep conceptual restructuring.

The expert panel validated the intervention’s potential to support multiscale reasoning and comparative methodology, recognizing these as critical components of geographical knowledge. While this formative phase focused on design quality and pedagogical coherence, the results provide a foundation for subsequent empirical testing. By extending place-based pedagogy to planetary contexts, the design offers a replicable model for geography education in an era of global and planetary uncertainty, reinforcing the discipline’s unique role in systemic, multiscale understanding of Earth and its planetary neighbours.

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Data Availability Statement: The data presented in this study are available on request from the corresponding authors. The full set of 10 misconception rules and corresponding feedback scripts for the AI tutor, Aristarchus, is available from the corresponding authors upon request.

Declaration of AI Tool Use: During the preparation of this manuscript, the authors used Gemini for the purpose of linguistic refinement. No AI-generated text was included in the conceptual development, data analysis, or interpretation of results. The authors reviewed and edited the content as needed and take full responsibility for the originality and integrity of the final published work.

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Contribution to the Special Issue Topics: This article contributes to the Special Issue [SI_TGEO] by addressing digital pedagogies and epistemic uncertainty. It operationalises a hybrid serious game model that integrates AR visualisations, game-based learning, and AI-supported feedback to restructure documented geographical misconceptions. By extending the comparative method to planetary contexts, the study provides a model for supporting macroscale spatial reasoning and helping students navigate complex environmental transitions within a framework of emerging planetary citizenship.

Appendix A

A.1. Rule-Based Feedback Architecture

Appendix A provides a structured representation of the rule-based feedback architecture to ensure methodological transparency regarding how documented misconceptions were operationalised within the system. This documentation is not intended as a technical specification but as evidence of alignment between disciplinary theory and instructional design.

Aristarchus is programmed to diagnose and scaffold ten persistent geographical misconceptions related to planetary atmospheres and the greenhouse effect. The agent employs a graduated feedback protocol: Hint (first response), Targeted Feedback (if the same misconception persists), and Full Explanation (after repeated errors or upon request). Table A1 presents two illustrative examples of the feedback logic; the full decision-tree and the complete set of ten rules are available from the corresponding author upon request.

Table A1. Operationalisation of Conceptual Change: Illustrative Feedback Scripts (examples)

Rule #	Misconception & Core Idea	Detection Logic / Verbal Patterns	AI Tutor Feedback Script
1	Confusion with Ozone: Believes the greenhouse effect and ozone hole are the same or directly cause each other. (Gautier et al., 2006)	Pattern 1: [ozone hole, ozone layer] + [cause, make, produce, is responsible for] + [global warming, climate change, greenhouse effect] Pattern 2: [CFCs, aerosol sprays] + [cause, create] + [greenhouse effect] Pattern 3: "fix the [ozone hole, ozone layer]" + "stop [global warming, climate change]"	I hear you mention the ozone layer. That's a common confusion! They're different: the ozone layer protects us from sunlight, while the greenhouse effect traps heat. Think of it like sunscreen versus a blanket. Would you like to explore how each works?
2	Entirely Bad Phenomenon: Believes the greenhouse effect is completely unnatural or harmful. (Gautier et al., 2006)	Pattern 1: [greenhouse effect] + [is bad, terrible, destructive, disaster] Pattern 2: [We should, we need to] + [eliminate, stop] + [greenhouse effect] Pattern 3: "without the greenhouse effect" + [we would be better]	You're right that the enhanced greenhouse effect is a problem. But the natural greenhouse effect is essential—without it, Earth would be a frozen planet! Imagine wearing one sweater vs. ten heavy coats in summer.

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