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An Embodied Digital Approach to Equitable Astronomy Education in Underserved Schools

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Abstract

Equitable science education not only requires access to schooling but also to the cultural tools and pedagogies through which contemporary science is practised. Astronomy is a revealing case because it demands complex visuospatial reasoning and is often taught through static textbook diagrams, particularly in resource-constrained settings. This study examines whether an integrated embodied digital astronomy module can broaden Grade 9 students' epistemic access in such settings. The module combined whole-body role plays, guided gestures, low-cost physical models, workbooks for student-generated diagrams, and carefully designed Hindi-medium simulations and games focused on the solar system and the Earth–Moon–Sun system. A quasi-experimental design was implemented in 14 rural Hindi-medium government schools in Rajasthan, with seven schools (169 students) using the module and seven schools (118 students) continuing with regular chalk-and-talk instruction. Pre- and post-tests assessed astronomy content knowledge, with an emphasis on visuospatial items, as well as attitudes and beliefs. Average scores of students from intervention schools increased from 33% to 47%, while those for students from non-intervention schools showed minimal gains (from 32.07% to 32.98%). The difference in gain scores for intervention schools was statistically significant. Improvements were strongest on spatial and explanatory items aligned with the embodied digital activities, and in the interventions students reported slightly more positive attitudes toward science and astronomy. Deeply held astrological beliefs showed little change over the short intervention. Classroom observations indicated a shift in intervention lessons from teacher-dominated recitation toward role plays, student diagrams, and interactive discussions around simulations, while non-intervention classrooms remained textbook-driven. The findings suggest that coordinated embodied digital pedagogy, designed for resource-constrained settings, can enhance both learning and participation in astronomy education. By providing access to interactive visualizations and collaborative activities traditionally unavailable in such contexts, the module offers a practical strategy for broadening epistemic access and addressing educational inequity, with potential applicability beyond the specific setting of this study.

Keywords: blended learning; digital activities; embodied activities; equity; access

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1. Introduction

Equitable science education is not only about bringing students into classrooms, but also about giving them meaningful access to the tools, representations, and practices through which contemporary science is done and learned. Astronomy is a powerful context to

examine this question because it is both highly engaging for young people and conceptually demanding (Lelliott & Rollnick, 2010), especially in terms of visuospatial reasoning and the coordination of multiple representations (Cole et al., 2018; Subramaniam & Padalkar, 2009).

1.1. Equitable Astronomy Education

Astronomy often invokes students' curiosity, yet research consistently shows that school students hold robust alternative conceptions about core topics such as occurrence of day and night, seasons, and lunar phases, and that these are difficult to change through conventional, lecture-based instruction (Bailey et al., 2004; Lelliott & Rollnick, 2010). Reviews of astronomy education have documented widespread misconceptions and limited progression in understanding across grades, as well as similar alternative conceptions among teachers, underscoring the need for targeted pedagogies in this domain (Blown & Bryce, 2010; Lelliott & Rollnick, 2010; Plummer, 2009a). In many educational contexts, including India, the conditions are not conducive to addressing these challenges. For example, in government schools, which is the site of the present study, classes are large, laboratories are minimal, and teaching is dominated by chalk-and-talk, textbook reading, and teacher questioning that leaves limited space for student exploration or discussion (Kozma & Vota, 2014; Sarangapani, 2003; Sarangapani et al., 2021). These constraints limit students' opportunities to engage meaningfully with astronomy concepts, creating a need for pedagogical interventions that can be implemented within such resource-constrained settings. In these, students usually encounter astronomy as static diagrams and memorized facts rather than as a domain that involves active modeling, reasoning with dynamic visualizations, and embodied engagement with spatial relationships (Galano et al., 2018; Lelliott & Rollnick, 2010).

At the same time, contemporary astronomy as a discipline depends heavily on digital simulations, visualizations, and data-rich environments to make sense of complex three-dimensional systems (Lan et al., 2021). Research on digital tools in science education suggests that well-designed visualizations can support learners' spatial reasoning and understanding of complex systems, but these resources are unevenly distributed and often unavailable in local languages in resource-constrained settings (Kozma & Vota, 2014; Sanchez & Wiley, 2017; Wagner et al., 2005). Embodied and interactive pedagogies, such as role plays and structured gestures, have also been shown to support conceptual change in topics that involve spatial thinking, including astronomy, by grounding abstract ideas in bodily experience and shared activity (Johnson-Glenberg, 2018; Nguyen & Larson, 2015; Plummer et al., 2016; Padalkar & Ramadas, 2010). However, these kinds of tools and pedagogical approaches are often unavailable in resource-constrained settings, where students from low-income and multilingual backgrounds have limited opportunities to engage with the representational practices central to contemporary astronomy (Butani, 2023; Kozma & Vota, 2014). This pattern raises a central equity concern: if equitable science education is understood as equitable epistemic access (Muller, 2014), then students in government schools should not only have a teacher and a textbook, but also opportunities to engage with the cultural tools, representations, and forms of activity that are central to how astronomy is currently practised and learned. Addressing this inequity requires practical, context-sensitive interventions that make such tools and pedagogies accessible in resource-constrained settings.

In this paper, equitable astronomy education is framed as a question of epistemic access for students in rural Hindi-medium government schools in Rajasthan, India. Our framing of equity in this paper focuses primarily on access: to schooling, to appropriate pedagogies, and to the tools and representations through which contemporary science is practised. We recognize that equity also involves deeper epistemic questions about whose

knowledge is valued and how cultural and social factors shape what counts as correct understanding. These questions are beyond the scope of the present study, but we see our work as complementary to efforts that engage with them more directly. The schools in this study face infrastructural constraints, such as limited numbers of functional computers, unreliable electricity, limited internet access, and a lack of context-specific digital resources in local languages, alongside broader systemic issues like overworked teachers and exam-driven curricula (Kozma & Vota, 2014; Lewin, 2007). Recent evidence from rural India documents that while smartphone penetration is high, as close to 90% of rural youth aged 14–18 have a smartphone at home and can use it, only 9% of households have a computer or laptop, and young women are more than twice as likely as young men to lack their own device (ASER Centre, 2024). Yet these same students bring rich everyday experiences of the sky, festivals (which fall on a specific phase of the moon), and local narratives about celestial bodies, which rarely find a place in classroom instruction. The study responds to this situation by designing and implementing an astronomy module that combines embodied activities and digital simulations in ways that are feasible in such schools and that explicitly aim to broaden students' access to powerful representations and practices in astronomy.

1.2. Research Aims and Questions

Most work on digital and embodied approaches has been conducted in well-resourced, often Western, classrooms. We developed a context-sensitive astronomy module through design-based research (Padalkar et al., 2020). In this study, we examined how this module would fare in resource-constrained, multilingual government schools in India, and how it might contribute to equitable science education.

We asked:

- RQ1: How effective is an embodied digital blended astronomy module in improving Grade 9 government school students' knowledge, beliefs, and attitudes toward astronomy, compared to traditional chalk and talk approach?
- RQ2: To what extent does this module support a shift in classroom culture toward more interactive, student-centred science teaching?

2. Theoretical and Literature Background

2.1. Astronomy Learning, Misconceptions, and Visuospatial Reasoning

Over five decades of research in astronomy education have documented that students hold robust alternative conceptions about core topics such as the shape of the Earth, day and night, seasons, lunar phases, and the motions of celestial bodies, and that these are resistant to change through traditional instruction (Bailey et al., 2004; Lelliott & Rollnick, 2010). Studies across different age groups and contexts show that students often internally construct coherent but scientifically incorrect models, for example, attributing seasons to changes in the Earth–Sun distance or lunar phases to Earth's shadow, and that these models can persist even after formal teaching (Blown & Bryce, 2010; Lelliott & Rollnick, 2010). In the Indian context, survey work with secondary students has reported high prevalence of such misconceptions and limited ability to connect factual knowledge with explanations of observable phenomena (Gali, 2021; Radhakrishnan, 2013).

A growing body of research links these conceptual difficulties to the demands that astronomy places on visuospatial thinking and the interpretation of multiple representations. Students must coordinate Earth-based perspectives with space-based perspectives, reason about three-dimensional arrangements and motions, and interpret diagrams, models, and graphs (Galano et al., 2018; Padalkar & Ramadas, 2010). Correlational studies indicate that spatial orientation, mental rotation, and spatial visualisation skills are associated

with better understanding of elementary astronomy concepts among secondary school students (Gali & Venukapalli, 2021). Similarly, Turk (2016) documented a high correlation between pre-service teachers' astronomy achievement and their skills for spatial thinking. Intervention studies have also shown that carefully designed representations, such as simplified and coherent images or structured use of models, can support more informed drawings and explanations of astronomical phenomena among students (Galano et al., 2018) and pre-service teachers (Plummer et al., 2010). Together, these works suggest that improving astronomy learning requires attention to both conceptual change and the spatial and representational resources available to learners.

2.2. Teachers' Astronomy Knowledge and Implications for Equity

Research on teachers' knowledge indicates that many in-service and pre-service teachers hold alternative conceptions similar to those held by students. Studies across different countries have found that teachers struggle with topics such as the causes of seasons, lunar phases, and the motions of celestial bodies, and often rely on memorized textbook information that is poorly connected to underlying mechanisms (Arslan & Durikan, 2016; Taşcan & Ünal, 2016; Turk, 2016). Analyses of teachers' mental models show that few hold fully scientific models, and many operate with non-adaptive or concrete models that lack relational understanding between concepts (Arslan & Durikan, 2016). These patterns are echoed in Indian studies that report limited depth in teachers' explanations of astronomical phenomena and low confidence in teaching astronomy topics (Sule & Jawkar, 2019).

In under-resourced contexts, these teacher knowledge gaps have particular equity implications. Government schools serving low-income and rural communities often offer fewer opportunities for subject-specific professional development, less access to up-to-date curriculum materials, and higher workloads, which make it difficult for teachers to experiment with new approaches (Kozma & Vota, 2014; Lewin, 2007; Centre of Excellence in Teacher Education [CETE], 2023). Students from rural communities face a linguistic barrier because their home language is often different from the textbook language and the medium of instruction, which is Standard Hindi. When teachers who are insecure about their understanding of astronomy rely on chalk-and-talk methods and textbook diagrams, then students who already face linguistic and material disadvantages are unlikely to gain access to the forms of reasoning and representation that characterize contemporary astronomy. Addressing teachers' conceptions and supporting their pedagogical content knowledge is therefore central to any equity-oriented intervention in astronomy education.

2.3. Digital Simulations as Contemporary Cultural Tools in Astronomy

Digital visualizations and simulations are now essential tools in professional astronomy, where they are used to model complex systems, explore dynamic processes, and analyse large datasets (Lan et al., 2021). In science education, digital tools can provide interactive, dynamic representations that are particularly well suited to supporting visuospatial reasoning, allowing learners to manipulate viewpoints, observe motions over time, and link multiple representations more easily than with static images alone (McElhaney et al., 2015; Sanchez & Wiley, 2017). Studies have shown that simulations and carefully designed visual resources can help students build more coherent models of astronomical phenomena, especially when combined with opportunities for discussion and reflection (Galano et al., 2018; Plummer et al., 2011).

However, access to such tools is unevenly distributed. In many resource-constrained contexts, schools have few functional computers, unreliable power supply, and limited connectivity, and available software is often not aligned with local curricula or languages (Kozma & Vota, 2014; Wagner et al., 2005). In India, for example, less than 20% of rural

schools and only 14% of government schools were connected to the internet in 2020/21, compared with about 50% of urban schools (UNESCO, 2023). Government schools in India commonly have computer labs that are underused or in disrepair, and teachers report a lack of appropriate digital resources in Indian languages as a barrier to the integration of technology in regular lessons (Balli & Singla, 2024; Chew & West, 2015). International experiences with large-scale initiatives such as One Laptop per Child and similar projects in the Global South show that simply providing hardware does not guarantee meaningful learning benefits, particularly when teacher support and context-specific resources are lacking (Bender et al., 2012; Mitra et al., 2005; Warschauer & Ames, 2010). From an equity perspective, this means that students in better-resourced schools, who use simulations and other visualization tools in science, gain access to powerful representational practices, while their peers in government schools often do not. The unequal distribution of digital simulations and visualizations thus becomes an epistemic and justice issue in astronomy education.

2.4. Embodied Cognition and Astronomy Pedagogy

Embodied cognition theories posit that cognitive processes are deeply grounded in bodily experiences, including perception, action, and sensorimotor engagement (Macrine & Fugate, 2021; Reid & Mgombelo, 2015; Shapiro, 2011; Varela et al., 2017). In science education, embodied pedagogy draws on this perspective to design learning environments where gestures, body movement, and spatial positioning are integral to knowledge construction rather than incidental to it (Gjengset et al., 2026; Johnson-Glenberg, 2018; Kersting et al., 2024; Nguyen & Larson, 2015). Astronomy concepts, which require learners to imagine themselves in different spatial locations and to track the relative positions and motions of celestial bodies, are particularly amenable to embodied approaches. Studies have shown that role-plays, gestures, and physical modeling activities can help students construct and manipulate mental models of systems such as the Earth–Moon–Sun, supporting conceptual change in topics like lunar phases and seasons (Rollinde et al., 2021; Rollinde et al., 2026; Padalkar & Ramadas, 2010). Euler et al. (2019) demonstrate how students used gestures and embodied enactment to reason about the orbital dynamics of a binary star system, interacting with each other against the dynamic backdrop of the PhET simulation *My Solar System* on an interactive whiteboard. Their analysis revealed that the body served as a central hub for coordinating multiple meaning-making resources—visual, gestural, and spatial—into coherent scientific explanations, even without relying on formal terminology. This highlights the power of embodied practices in supporting deep, multimodal understanding of complex astronomical phenomena.

Embodied approaches are also relevant for multilingual classrooms. When the medium of instruction differs from students' home languages, as is often the case in Indian government schools, students may struggle to express and refine their ideas using only the language of schooling. Embodied activities provide additional representations through which students can participate in sense-making, drawing on shared bodily experiences and spatial reasoning even when verbal explanations are challenging (Nguyen & Larson, 2015). Moreover, embodied activities can be implemented with minimal physical resources, for example, by using students' bodies, simple props, and classroom space, as they are feasible in schools with limited equipment, thus making them a just and egalitarian resource. For these reasons, embodied pedagogy has significant potential as an equitable strategy for supporting diverse learners in understanding spatially demanding astronomy concepts.

2.5. Integrating Embodied and Digital Approaches for Equitable Epistemic Access

The literature on digital simulations and on embodied pedagogy in astronomy has largely developed in parallel. Many studies focus on the benefits of digital tools or of embodied activities separately. However, these two approaches tap the potential of two different but complementary forms of engagement, one providing interactive visualizations and the other grounding concepts in bodily experience, which together build our understanding of space, and hence are the basis of visuospatial thinking (Johnson-Glenberg, 2018). Thus, a combination of these approaches should lead to a richer and more in-depth understanding of astronomy and potentially other topics that rely on visuospatial thinking (Lindgren et al., 2016).

Moreover, most intervention work has been conducted in relatively well-resourced settings, such as small classes in high-income countries, university courses, or special programs like camps and planetarium visits (Fields, 2009; Galano et al., 2018; Plummer, 2009b). There is comparatively little research on coordinated designs that deliberately integrate embodied and digital elements in the same module and examine how this integration can support learners in under-resourced, multilingual government schools.

This study addresses that gap by treating embodied activities and digital simulations as complementary components of a single embodied–digital pedagogy for astronomy. The design aligns whole-body enactments, gestures, and manipulation of physical models with carefully created and curated digital visualizations, so that students can move between bodily experiences and screen-based representations of the same phenomena. From an equity standpoint, this integration is not only a design choice but also an epistemic access strategy. By bringing together contemporary cultural tools of astronomy, such as simulations and dynamic visualizations, with embodied, low-cost activities that are feasible in rural government schools, the intervention seeks to broaden students' opportunities to engage with the forms of reasoning, representation, and participation that characterize modern astronomy.

3. Context and Participants

3.1. Educational Context

The study was conducted in government secondary schools in the Indian state of Rajasthan, in and around the city of Jaipur (Figure 1). In official documents and in everyday use by local educators, the medium of instruction in these schools is described as "Standard Hindi," while most students' mother tongues are regional varieties of Rajasthani (like Marwari, Mewari, and Dhundhari). The term "Standard Hindi" is used here to reflect local naming practices, not to imply that there is a single correct or neutral form of Hindi. The home languages that students speak are treated as legitimate and fully fledged linguistic resources, not as deficient versions of the school language.

These schools serve students from low socio-economic backgrounds, with limited access to scientific materials beyond the state textbook and very little exposure to digital resources outside school. School infrastructure reflects the broader constraints of the government system: minimal laboratory facilities, and computer laboratories with at most ten government-provided computers, many of which are not always functional. Electricity and internet connectivity are limited, which restricts the use of online resources and places practical constraints on computer use during regular lessons. Students' exposure to computers is recent and largely confined to activities initiated through the Connected Learning Initiative (CLIx). Prior to this, they had little or no experience using digital tools for learning science. These conditions are typical of rural and peri-urban government schools in the region and shape students' epistemic access to contemporary tools and representations in astronomy.

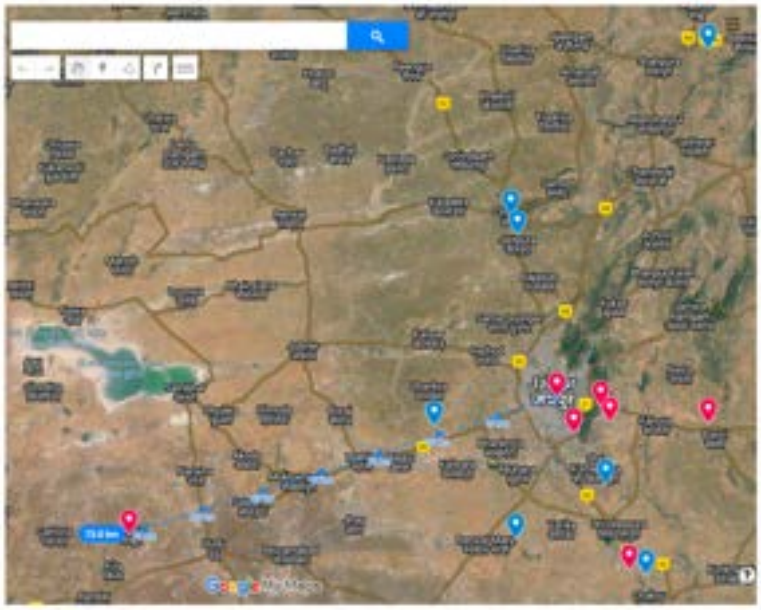


Figure 1. This map displays the distribution of intervention (blue pins) and comparison schools (red pins) across the study area in Rajasthan, with the farthest school located approximately 73 km away from Jaipur. (Image credit: Google Maps).

3.2. Schools, Teachers, and Students

Schools for the intervention were selected using four criteria. First, the number of students in the focal Grade 9 class had to be less than 40 so that embodied activities and group work could be managed by a single teacher and the class could be split into at most two batches for computer-laboratory sessions. Second, the school computer laboratory had to have at least nine working terminals, ensuring that a batch of about 20 students could access digital activities using a buddy system[1]. Third, science teachers needed to be at least open to trying new pedagogies. Drawing on prior experience with in-service teacher education in Rajasthan, the research team and local field partners invited teachers who were not openly opposed to such work and who were willing to attend workshops, even if they were cautious or sceptical. Finally, schools had to be within approximately 80 km of Jaipur, where the project office was located, so that researchers could conduct regular classroom observations and provide in-school support.

Thirteen science teachers from 13 government schools in Jaipur and nearby villages were initially invited to a preparatory workshop. Ten teachers attended the workshop; two subsequently indicated that they would not be able to participate in the study, and one school had to be dropped mid-study because the teacher went on an extended leave, leaving seven intervention schools that completed implementation. Seven additional government schools from the same area, with similar profiles but without the astronomy module, were selected as non-intervention schools (Table 1). A total of 219 students were enrolled in the intervention schools and 236 were enrolled in the non-intervention group. However, for data analysis, we selected the students who were present for both pre- and post-tests (Table 1).

Table 1. Number of teachers and students (who attempted both pre- and post-test) in intervention and non-intervention groups.

	Intervention	**Non-Intervention**
Teachers	7 (4 female, 3 male)	7 (4 female, 3 male)
Students	169 (100 girls, 69 boys)	123 (82 girls, 41 boys)

Most participating teachers were from upper-class and traditionally dominant-caste backgrounds, lived in Jaipur, and commuted to schools, particularly when the schools were located in nearby villages. In informal conversations, several teachers noted that their own social and economic backgrounds differed markedly from their students and indicated that they perceived themselves as different from the communities they served, which was generally reflected in low expectations of students' academic capabilities. Teachers also shouldered substantial administrative and managerial responsibilities, including data collection for government surveys, supervision of the mid-day meal scheme, and organisation of school events, in addition to teaching, preparing examinations, and grading. In many schools, the number of teachers was below sanctioned levels, increasing both teaching and non-teaching workloads. These conditions limited the time and energy teachers could devote to lesson preparation and made them hesitant to adopt approaches they perceived as risky, time-consuming, or misaligned with exam pressures, including interactive and technology-supported pedagogies.

4. Design of the Embodied–Digital Astronomy Module

4.1. Design Principles for Equity

The astronomy module was developed as part of a larger technology-enabled initiative called the Connected Learning Initiative (CLIx): https://clix.tiss.ac.in/, (accessed on: 22 October 2026) designed for high school students, which developed blended modules in English, mathematics, and science for Grades 8 and 9 in multiple Indian languages. Since these modules were designed to be implemented by teachers in their respective schools, it was a requirement of the initiative that the core content align broadly with the textbooks. However, instead of restricting the module to Grades 8 and 9, it incorporated foundational content from earlier grades because students often learn this material superficially, without developing a coherent mental model or applying it to explain basic phenomena like day and night. This foundational understanding is essential for grasping more complex concepts, such as seasonal changes. Textbooks from Grades 5 to 9 include basic information about the Earth, the Moon, the Sun, and the rest of the solar system; introduce prominent constellations; and explain key phenomena such as day and night, seasons, phases of the Moon, and eclipses. The astronomy module is published as an open educational resource and can be accessed here: <https://clixplatform.tiss.ac.in/home/module/59816df569602a015784baea/courses> (accessed on: 22 October 2026).

The two main pedagogical pillars for this module were embodied activities and digital activities, which are elaborated in the next two subsections.

4.2. Embodied Components

Astronomy concepts such as day and night, seasons, and lunar phases require learners to reason about three-dimensional arrangements and motions. The module, therefore, placed strong emphasis on embodied activities that engage students' visuospatial resources (see Figure 2 for examples). Across the three units of the module (Earth, Moon, Solar System), lessons included manipulating concrete models, guided gestures, and role-plays, along with a deliberate focus on spatial representations such as diagrams and photos. For example, a "geosynchron" model (proposed by Monteiro et al., 2007), consisting of a globe mounted so that its axis is parallel to the actual axis of the Earth, was used under direct sunlight to help students observe time of day at different locations and relate these observations to the Earth's rotation. Gestures, such as using the right-hand thumb rule to indicate the direction of rotation, were explicitly taught and rehearsed to support the construction of consistent spatial images.



Figure 2. Examples of embodied activities used in the astronomy module. (**A**) Students and the teacher enact the Earth–Moon–Sun system through a role-play. (**B**) The teacher demonstrates a gesture to indicate the fixed position of the Pole Star, with one student mimicking the gesture while classmates observe.

Role-plays were extensively used to enact the motion of the Earth and Moon around the Sun. Some classrooms did not have benches, and the students sat on mats on the floor; others had open spaces such as playgrounds or terraces where students could move around to do the role-plays. Students physically moved around the classroom, taking on positions as celestial bodies and observers, while their peers and the teacher discussed what would be seen from different vantage points. Diagrams were woven throughout these activities: students copied diagrams, interpreted them, and drew their own representations of phenomena such as day and night or the phases of the Moon from different perspectives. These embodied components were designed to be feasible in resource-constrained classrooms, relying on low-cost materials and students' bodies, while providing multiple spatial routes into core astronomical ideas.

4.3. Digital Components

The digital part of the module was designed to complement and extend the embodied activities by providing dynamic visualizations and interactive games that would otherwise be unavailable in these schools. Each of the three units included one digital lesson, for a total of three digital lessons across the module. All digital lessons had two parts. In the first part, students engaged with animations that showed the relevant astronomical system from multiple perspectives and highlighted key motions. In Unit 1, the animation sequence focused on the rotation of the Earth; Unit 2 included an animation of the revolution of the Moon around the Earth; and the third focused on the structure of the solar system. In some cases, animations morphed into schematic diagrams similar to those found in textbooks, explicitly linking dynamic screen-based representations to the static diagrams students commonly encounter.

The second part of each digital lesson consisted of a level of the game AstRoamer, designed in-house to help students apply and consolidate their understanding. In Unit 1, "AstRoamer: What's the time?" focused on the Earth's rotation and time of day at different locations; in Unit 2, "AstRoamer: Moon Track" focused on phases of the Moon; and in Unit 3, "AstRoamer: Planet Trek" focused on characteristics of planets and their orbits. Each game sequence included demonstrations and a series of problems, with two chances per trial and tailored feedback after incorrect first attempts. The digital lessons were developed with principles from computer-supported collaborative learning and multimedia learning in mind, for example, segmenting content, coordinating visuals and text, and encouraging joint problem solving at the computer. Crucially, the games were designed with a buddy

login system so that two students could answer alternately, with turn-taking and discussion built into the interaction with the software. Screenshots of digital activities and a glimpse of a pair of students accessing them in a computer lab are shown in Figure 3.

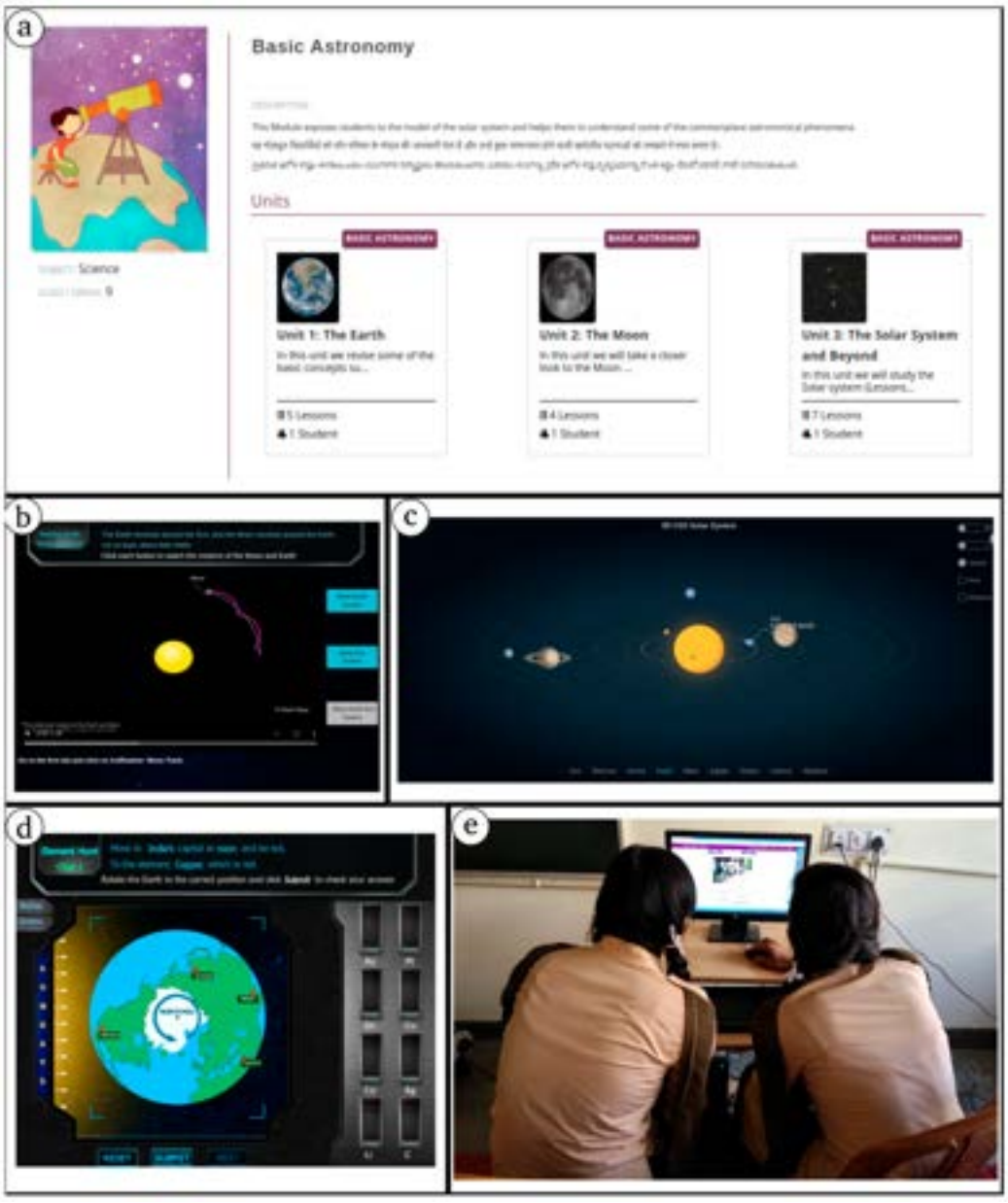


Figure 3. (**a**) Screengrab from the landing page of the Basic Astronomy module, all three units are visible; (**b**) Example of animation showing the Sun, Earth and Moon system; (**c**) Example of simulation showing solar system which can be manipulated using buttons in the top right corner; (**d**) Example of digital game called AstRoamer, this is from unit 1, similar games are in other two units as well; (**e**) Photograph showing two students working on a terminal using buddy-login (an innovation designed to enable two students sharing a computer).

4.4. Coordinating Embodied and Digital Activities

A central design decision was to coordinate embodied and digital activities so that they addressed the same concepts from complementary angles rather than as separate, unrelated experiences. The module was organized into three units (Earth, Moon, Solar System), each with four lessons: three classroom lessons and one digital lesson (see Figure 4). Classroom lessons typically followed a sequence in which students first manipulated

concrete models, then used gestures and role-plays to enact motions, and then worked with diagrams and photos. The corresponding digital lesson then revisited the same concepts through animations and AstRoamer games, allowing students to see dynamic visualizations of phenomena they had previously enacted with their bodies and drawn in their workbooks.

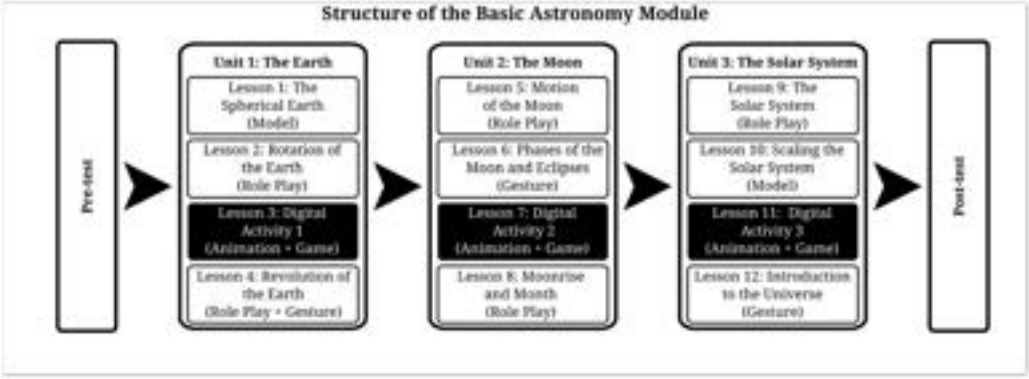


Figure 4. Structure of the Basic Astronomy Module.

For example, in the unit on the Earth, students used the geosynchron model, gestures, and role-plays to understand rotation and day–night patterns before playing "AstRoamer: What's the time?" in the computer lab. Similarly, in the unit on the Moon, classroom activities on phases of the Moon and eclipses preceded the "AstRoamer: Moon Track" game, which was designed around phases associated with local festivals to connect school astronomy with students' cultural calendars. This deliberate sequencing was intended to help students move between embodied experiences, concrete models, diagrams, and digital visualizations, thereby strengthening their mental models and supporting transfer.

The design also incorporated specific moves to address resource constraints while maintaining equitable access to digital components. The module was pre-installed on a local server to run offline, reducing reliance on unstable internet connectivity. These choices allowed students in rural government schools, who would otherwise have little or no exposure to simulations and interactive visualizations in science, to participate in technologically rich activities that are more common in better-resourced settings.

5. Teacher Preparation and Support

5.1. Teacher Workshops

Given prior evidence that many science teachers hold alternative conceptions in astronomy, teacher preparation was treated as a central component of the intervention rather than an add-on. Two day-long workshops were conducted, one before the start of classroom implementation and another midway through the module. In both workshops, teachers engaged with the selected activities of the same embodied–digital astronomy module that their students would later experience, but in the role of learners. This approach was intended to address teachers' own content understandings and to model the pedagogy of integrating concrete models, role plays, gestures, diagrams, animations, and digital games.

In the first workshop, it became evident within the first hour that teachers themselves had significant difficulties with basic astronomy concepts, such as the causes of seasons and phases of the Moon. Teachers were invited to participate in activities, for example, role-plays explaining why only one face of the Moon is visible from Earth, and to articulate their explanations. Many teachers initially offered familiar but incorrect explanations, and several expressed surprise when these were identified as misconceptions. The activities led to visible "aha" moments for some participants, who acknowledged that the embodied tasks and visualizations helped them make sense of ideas they had previously been taught

in a rote manner. At the same time, teachers voiced concerns about the time required to implement the module and about their students' ability to cope with what they perceived as advanced explanations. The workshop, therefore, served both as a space for conceptual learning and as an opportunity to begin negotiating tensions between exam-driven routines and more exploratory pedagogy.

The second workshop took place after teachers had implemented approximately half of the module. Attendance and punctuality were higher, which was interpreted as a sign of growing commitment. The workshop began with a structured sharing of experiences: teachers reported that students were engaged, enjoyed the activities, and participated more actively than usual. Aggregate results of the pre-test were then presented, focusing on item-level patterns and common misconceptions rather than school-wise comparisons, to avoid singling out individual teachers or schools. The selected activities of the remaining module were then enacted with teachers again, with the same embodied–digital approach, followed by open discussion of challenges, questions, and adaptations. The workshop concluded with a reflective discussion of the purposes of science education, emphasizing reasoning and understanding over memorization.

5.2. In-School Mentoring and Adaptation

Based on our prior experience (Shaikh et al., 2018), workshops alone were not expected to be sufficient for sustained change in practice, particularly given teachers' workloads and initial hesitation about interactive and technology-supported methods. The research team therefore provided ongoing in-school mentoring throughout the implementation period. During the first six working days after the initial workshop, teachers were asked to teach approximately one lesson of the module per day. Researchers visited classrooms on a rotating basis to observe lessons, provide on-the-spot support, and document how the embodied and digital activities were enacted.

Before key lessons, researchers contacted teachers by phone or messaging to remind them which activities and concepts were to be covered and to share links to short videos demonstrating classroom activities, such as role plays. In observed lessons, researchers sometimes co-planned or co-facilitated segments, particularly early in the implementation, and gradually reduced their direct involvement as teachers became more familiar with the module. After each observed lesson, brief debriefing conversations were held in which researchers highlighted specific strengths, such as successful facilitation of a role play or an effective adaptation of a diagram, and gently pointed out issues, such as skipped activities or content errors. These conversations focused on concrete suggestions for improvement and on encouraging teachers to see students' questions and incorrect responses as opportunities for further exploration. Teachers' initial resistance was evident in their concerns about losing control of the class during role plays, spending too much time on a single chapter, or confusing students with what they saw as overly detailed/advanced explanations.

6. Methods

6.1. Research Design

The study followed a quasi-experimental, mixed-methods design with an intervention group and a non-intervention group in matched government schools. In the intervention schools, Grade 9 science teachers implemented the embodied–digital astronomy module as part of their regular teaching of the astronomy chapter. In the non-intervention schools, teachers taught the same textbook content using their usual chalk-and-talk methods. Both groups completed the same pre-test prior to astronomy teaching and an equivalent post-test once astronomy teaching was completed (see Figure 5). Assessment items related to indigenous astronomy (see Appendix A for cultural context) included questions about

Nakshatras (lunar mansions), lunar phases, and festival associations. For the intervention group, the design also included teacher workshops, classroom observations, and ongoing support during the implementation period. For the non-intervention group, selected lessons were observed to document typical instructional practices.

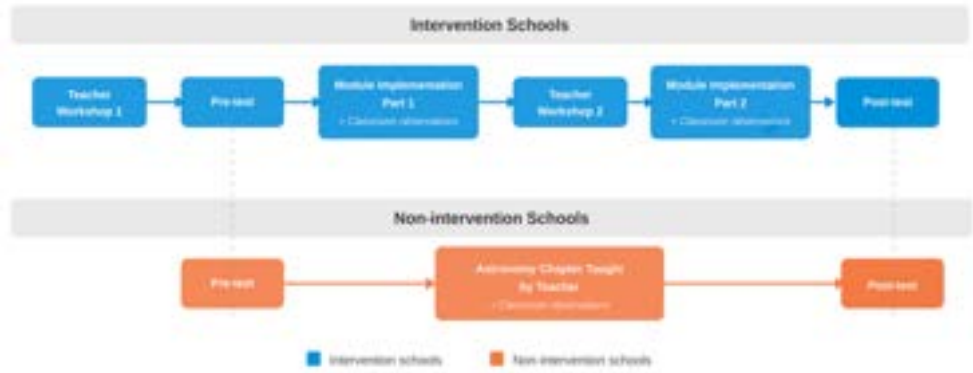


Figure 5. Timeline of the study.

6.2. Instruments

The pre-test was a 27-item questionnaire, and the post-test was a 32-item questionnaire that included questions on astronomy content, attitudes, aspirations, and beliefs. English translations of the original Hindi questionnaires are given in Appendix B.

6.2.1. Astronomy Content Assessment

The main quantitative measure of learning was an assessment of astronomy content administered before and after instruction. The assessment included multiple-choice and true–false items targeting key astronomy concepts from the curriculum, such as day and night, seasons, phases of the Moon, eclipses, and basic features of the solar system. A subset of items was explicitly designed to tap visuospatial reasoning, for example, interpreting diagrams of the Earth–Moon–Sun system, predicting what an observer would see from different positions, or choosing diagrams that corresponded to verbal descriptions. Items were adapted from the Astronomy Diagnostic Test (Collaboration for Astronomy Education Research, 2004) and from instruments developed in earlier research on astronomy learning, with modifications for alignment with the Grade 9 syllabus and were in Hindi for linguistic clarity. The pre-test contained 19 content items (4 true–false, 15 multiple-choice) and one diagram item, and the post-test contained 25 content items (5 true–false, 19 multiple-choice) and the same diagram item, with additional items focusing on concepts covered more extensively in the module.

6.2.2. Attitude and Aspiration Measures

To capture affective and motivational dimensions, the assessment also included items on students' attitudes toward science and astronomy and their aspirations related to future study or careers in science. These consisted of four Likert-scale items (for example, agreement with statements about liking science or wanting to learn more astronomy) and one item where students chose among options representing different aspirations (for example, whether they would like to study science further). The same attitude and aspiration items appeared in both pre- and post-tests. Because many students had limited prior experience with Likert-type questions, the items were piloted with a similar student population and revised for clarity, and teachers were given brief instructions on how to explain the response format.

6.2.3. Belief Items

A small set of items addressed beliefs related to astronomy and astrology, such as views about the influence of celestial bodies on human affairs or the nature of astrological claims. These included one true–false item, one Likert-scale item, and one item where students chose among explanatory options. The goal was not to comprehensively assess belief systems but to obtain an initial indication of whether the module had any short-term influence on students' willingness to question astrological explanations of celestial phenomena. These items were included in both pre- and post-tests.

6.2.4. Observation Protocols and Field Notes

Qualitative data was collected to document classroom practices and teacher and student experiences. Structured observation protocols were used during lessons in intervention and non-intervention schools to record features such as the types of activities used (lecture, question–answer, practical work, role-plays), the use of diagrams and models, and the extent of student participation. In intervention schools, observations focused particularly on how teachers enacted embodied activities and digital lessons, how students engaged with these components, and how classroom norms evolved over time. Five to six classes were observed in each of the intervention schools and two classes were observed in each of the non-intervention schools. This matched the total duration for teaching the chapter on astronomy in most schools.

In addition, discussions with teachers were conducted at multiple points to explore their understanding of astronomy, their perceptions of the module, and their experiences with implementation. Researchers also maintained detailed field notes from school visits, including informal conversations with teachers and students, contextual information about school routines, and reflections on emerging themes. These qualitative sources were used to complement and interpret the quantitative findings.

6.3. Data Collection Procedures

Data collection took place over one instructional unit on astronomy in each school. The pre-test was administered in both intervention and non-intervention schools before any astronomy instruction began. Assessments were administered in regular classrooms as paper–and–pencil instruments, with a maximum of 45 min allowed; all students completed the assessment within this time.

In intervention schools, the embodied–digital astronomy module was then implemented by the participating science teachers, typically over approximately two weeks of regular school time, with one lesson taught per working day. Researchers visited schools during this period to observe selected lessons, support teachers, and monitor implementation fidelity, for example, whether key activities were conducted as intended and whether the digital lessons were used as planned. In non-intervention schools, teachers taught the astronomy chapter using their usual methods over a similar time frame, and researchers observed a sample of lessons to characterise regular instruction.

The post-test was administered in both groups within a few days of completing instruction on astronomy, using the same procedures as the pre-test. Observation notes and field notes were collected throughout the implementation period. All data was anonymized and stored securely.

Data Analysis

The quantitative analysis focused on comparing learning gains and changes in attitudes and beliefs between intervention and non-intervention schools. For the astronomy content assessment, total scores and subscores (for example, items requiring visuospatial reasoning)

were calculated for each student at the pre-test and post-test time points. Descriptive statistics were computed, and change scores (post-test minus pre-test) were compared between groups using appropriate inferential tests. Effect sizes were calculated to quantify the magnitude of differences. Item-level analyses were conducted to examine patterns of change on specific questions, particularly those targeting common misconceptions and spatially demanding tasks.

For the attitude and aspiration items, Likert-scale responses were combined into an index, and changes from pre-test to post-test were compared across groups. Responses to belief items were analyzed descriptively to see whether the distribution of answers shifted after the intervention.

Qualitative data from observations, discussions with teachers, and field notes were analyzed using thematic coding. An initial coding scheme was developed based on the research questions and on constructs from the literature, such as student participation, types of questions asked, use of embodied and digital activities, and teacher positioning of students' ideas. Codes were refined iteratively as transcripts and notes were reviewed. Patterns were identified within and across schools regarding how teachers enacted the module, and how classroom culture shifted. The quantitative and qualitative findings were then brought into dialogue to provide a richer account of how the embodied–digital module functioned as an equity-oriented intervention in these government school classrooms.

7. Findings

This section presents findings for the two research questions. RQ1 examines the effectiveness of the embodied digital astronomy module in improving the students' knowledge, attitudes, and beliefs. RQ2 examines whether and how the module supported a shift toward more interactive, student-centred classroom practices, provided teachers received continuous professional development throughout the implementation of the module. We also provided a description of classroom practices in non-intervention schools to set a background. For RQ1, we first report overall test scores for intervention and non-intervention schools, then present item-level patterns, followed by changes in attitudes and beliefs. Only students who completed both the pre- and post-test are included in the analyses. For RQ2, we draw on classroom and computer-lab observations and field notes of the intervention and non-intervention school to characterize changes in classroom culture.

7.1. Effectiveness of the Module

7.1.1. Comparison Between Intervention and Non-Intervention Schools

Since the maximum possible scores for the pre- and post-tests were different, all the scores were converted into percentages. The average percentage for each school for the intervention group is provided in Table 2, and that for the non-intervention group is provided in Table 3.

As seen in Tables 2 and 3, the average percentage in the pre-test of both groups was about 33.31 and 32.07%, which is very low. This low starting point indicates that students in these government schools had limited conceptual access to basic astronomy ideas, despite having formally studied astronomy in previous years. In terms of equitable science education, this highlights that mere access to schooling does not automatically translate into epistemic access to core models and representations in astronomy and likely extends to other science topics as well.

The difference between pre-test scores for the intervention schools and non-intervention schools was not statistically significant ($p = 0.88$). So the intervention and the non-intervention groups were equivalent.

Scores of the students from intervention schools significantly improved after the intervention ($p < 0.001$), whereas those in the non-intervention group did not improve significantly ($p = 0.10$).

Not only is the difference between pre-test scores of intervention and non-intervention groups significant but the difference in improvement between intervention and non-intervention groups is also significant ($p < 0.001$). The average Post-test score for the intervention group is only about 47%, so there was scope for more improvement. Note, however, that the post-test included 5 advanced questions.

Table 2. Statistics for Intervention Schools.

Name of the School	n (Actual)	n (Paired)	Average % Score on Pre-Test (S.D.)	Average % Score on Post-Test (S.D.)	Effect Size	*p* Value
School A	21	18	27.50 (8.45)	36.67 (12.29)	0.82	0.0033 **
School B	42	34	42.79 (11.36)	74.00 (6.17)	1.73	0.000 ***
School C	40	34	30.74 (12.01)	38.12 (11.95)	0.6	0.0007 ***
School D	34	28	33.75 (11.11)	40.43 (10.80)	0.59	0.059
School E	25	22	32.5 (11.73)	46.91 (12.60)	1.04	0.0003 ***
School F	41	24	27.92 (14.21)	37.17 (11.03)	0.70	0.004 **
School G	16	9	33.89 (13.41)	38.22 (10.22)	0.38	0.366
All schools together	219	169	33.31 (12.71)	46.58 (17.63)	0.79	0.000 ***

(*** difference significant at $p < 0.001$; ** difference significant at 0.01; * difference significant at 0.05).

Table 3. Statistics for Non-Intervention Schools.

Name of the School	n (Actual)	n (Paired)	Average % Score on Pre-Test (S.D.)	Average % Score on Post-Test (S.D.)	Effect Size	*p* Value
School H	43	23	30.65 (7.28)	29.91 (8.17)	−0.097	0.683
School I	33	15	32.33 (10.67)	33.33 (9.52)	0.102	0.743
School J	20	14	33.21 (9.32)	34 (7.65)	0.096	0.742
School K	60	29	32.24 (11.69)	36 (10.47)	0.34	0.177
School L	23	12	33.33 (9.85)	30.33 (7.13)	−0.359	0.311
School M	26	15	24.67 (5.50)	35.73 (9.25)	1.203	0.000 ***
School N	31	15	39.33 (11.00)	29.87 (11.10)	−0.81	0.002 *
All schools together	236	123	32.073	32.976	0.09	0.405

(*** difference significant at $p < 0.001$; ** difference significant at 0.01; * difference significant at 0.05).

Notice that the Table 3 shows that School M's post-test scores were notably higher than those of other non-intervention schools. We discuss this in more detail in Section 7.2.

The significantly larger gains in the intervention group show that when students in government schools are given structured access to embodied activities and digital visualizations, their conceptual understanding can improve beyond what is typically achieved through chalk-and-talk methods. This suggests that inequalities in learning outcomes are at least partly a function of unequal access to powerful pedagogical approaches and representational tools, rather than inherent differences in student ability.

7.1.2. Item-Level Analysis

The item-level analysis shows that students entered the module with a very uneven astronomy knowledge profile across the 19 content items. Only on two items did a clear majority of students answer correctly on the pre-test. Specifically, 63.9% knew that gravitational force keeps the Moon in orbit around the Earth and 62.7% recognized that a galaxy is not part of the solar system. On most other items, fewer than 60% answered correctly. There were strong misconceptions about observations, mental models, explanations, and

indigenous knowledge. For example, 92% believed the Sun comes overhead every noon. About 70% did not know Saturn is visible to the naked eye. Only 2% could correctly name Sirius as the brightest star. On spatial items, 24% located the asteroid belt between Mars and Jupiter. 19% ordered Moon–Earth–Saturn–Sun correctly by size. 18% ordered Moon–Sun–Uranus–Pole Star correctly by distance. Explanatory items were also difficult. 19% correctly attributed day–night to Earth's rotation and 17% attributed seasons to the tilt of Earth's axis. 39% instead chose Earth's revolution or elliptical orbit. Only 19% identified a star as self-luminous while 56% chose the Moon. Performance on questions related to indigenous knowledge was also low. 25% correctly identified *Rohini* as a *nakshatra* (Lunar mansion) while 28% misidentified *Makara* (Capricorn), a *rashi* (zodiac), as one. Overall, the pre-test suggests limited systematic sky observation, fragmented factual knowledge, and weak spatial mental models and explanations.

After the intervention, students in the intervention group improved on 14 of the 19 content items. They regressed on 5 items. Gains were most notable on spatial and explanatory items that were taught through coordinated role plays, diagrams, and digital activities. Correct responses for day–night as due to Earth's rotation rose from 19% to 36%. The major alternative conception, that it occurs due to revolution around the Sun, dropped from 48% to 12%. Correct responses for seasons due to Earth's tilted axis increased from 17% to 33%. The elliptical orbit misconception decreased from 39% to 22%. Correct ordering by size improved from 19% to 35%. Correct ordering by distance improved from 18% to 34%. Understanding that stars are self-luminous increased from 19% to 60%, while choosing the Moon as a self-luminous object dropped from 56% to 26%. Items tied more to direct observation or indigenous knowledge showed weaker gains or regression. Accuracy on terms like *Shukla Paksha* (waxing phases) and *Krishna Paksha* (waning phases) or festival phase associations decreased. These topics appeared in the digital activities but without systematic observation tasks. This reflects a design trade-off. Night sky observations and detailed indigenous knowledge were largely omitted for feasibility reasons, even though they informed some items. Overall, the item-level results suggest that the embodied digital module, in comparison with the chalk-and-talk approach, was particularly effective in strengthening spatially rich models and mechanistic explanations, while offering less support on observational and indigenous knowledge aspects that were not explicitly foregrounded.

7.1.3. Attitudinal Questions

Out of five questions related to students' attitude towards science in general (e.g., I enjoy learning science.) and astronomy in particular (e.g., I find astronomy interesting). Four questions elicited responses on the Likert scale (1 to 4). One was a check-box question in which various aspects of astronomy, such as observations, instrumentation, or history of astronomy, were given as checkboxes to the prompt: "In the future, I would like to engage in…".

We calculated a single score for each student based upon the responses to all attitudinal questions. It is the sum of the answers to the four questions on the Likert scale and the number of check-boxes they ticked for things in astronomy that interest them (we did not include the point for interest in astrology if they marked the answer that astrology interests them). The maximum possible score for attitudinal questions is 28. The scores for pre- and post-test are converted into percentages and are given in Table 4.

As seen in Table 4, the average pre-test scores of the intervention and non-intervention groups were very similar. However, for the post-test, the scores significantly increased (with a small effect size) for the intervention group and significantly dropped for the non-intervention group. Thus, according to students' self-reports, the module helped to improve students' interest and attitudes towards science and astronomy, whereas regular teaching in the non-intervention schools slightly worsened students' interest and attitudes towards science and

astronomy. The study shows that it is possible to sustain, and even enhance, students' interest in astronomy when they are invited to participate in more interactive, tool-rich forms of learning. This is important from an equity perspective because if students have positive dispositions toward astronomy and science, they are more likely to maintain a positive attitude toward them in the future (Ing & Nylund-Gibson, 2017).

Table 4. Average scores and standard deviations (in percentages) on attitudinal questions.

	Pre-Test Score (SD)	Post-Test Score (SD)	t	df	*p*	Cohen's d
Intervention	65.89 (18.19)	69.55 (16.46)	2.3	168	0.02 *	0.21
Non-intervention	63.53 (14.76)	59.38 (14.50)	3.1	117	0.002 **	−0.28

(** difference significant at 0.01; * difference significant at 0.05).

7.1.4. Belief Change

The module connects indigenous knowledge to observational astronomy wherever possible, so that textbook knowledge does not remain disconnected from students' cultural lives. Many of the terms used in indigenous astronomy are common with astrology as well. By explaining these terms, we hoped that the mysterious aura around them would be dispelled and the students would be able to think rationally about them.

The tests had three explicit questions and discussions around this. As shown in Table 5, the percentages of students who believed in a superstition related to astrology decreased from pre-test to post-test for the intervention group and increased for the non-intervention group. Although the two groups showed very different profiles before the intervention, the percentage of students who would like to engage in horoscopes and astrology in the future decreased for the intervention group and increased for the non-intervention group after the intervention.

Table 5. Percentage of students who believe in astrology.

	Pre-Test	Post-Test
	Eclipses are bad omens and should not be seen	If you make a wish while watching a shooting star, it comes true
Intervention	55.62	47.93
Non-intervention	49.15	59.32
Percentage of students who would like to engage in horoscopes and astrology in the future		
Intervention group	29.59	26.04
Non-intervention group	13.56	16.95
The percentage of students who believed that planets can influence our lives in a supernatural way		
	Pre-test	Post-test
Intervention group	52.66	57.99
Non-intervention group	43.22	42.37

Table 5 shows that, to begin with, a larger percentage of students from the intervention group believed in astrology than the non-intervention group before the intervention. This

percentage further increased among the intervention group after the intervention but slightly reduced for the non-intervention group. Thus, the module was not successful in changing the students' deeply held belief that planets can influence our lives in a supernatural way.

Together, analysis of three questions showed mixed results, but we can conclude that the module only moderately influenced students' beliefs. This limited change is not surprising, given that beliefs about astrology and celestial influences are woven into broader cultural and community discourses. It suggests that meaningful astronomy education cannot be reduced to short, de-contextualized interventions, but requires sustained engagement with students' and communities' ways of knowing, and institutional support for critical discussion of scientific and non-scientific explanations.

7.2. Classroom Culture and Student Agency

In this section, based on systematic classroom observations, we provide a description of pedagogy in non-intervention schools so that it helps readers draw a contrast between the two groups.

7.2.1. Pedagogy in Non-Intervention Schools

The prominent pedagogy in the non-intervention schools was reading from the textbook and elaborating on it when the teacher felt necessary, with occasional variation when teachers asked a student to read aloud or copy definitions from the board. Only two teachers (Schools I and N) were exceptions, teaching more independently with better content knowledge and confidence.

All teachers asked questions (10 to 30 per lesson), typically beginning with a broad question (e.g., "What do you see from your terrace?"), followed by textbook reading and elaboration. Most questions were rhetorical (e.g., "Have you heard of Mangalyaan?") or answerable in one word (e.g., "Which is the nearest planet?"). When students knew the answers, they raised their hands and answered; if not, teachers repeated the question and then told the answer or read from the textbook. Two exceptions were noted: one teacher provided hints, and another waited for students to answer. Teachers usually began the second class with questions on previous content, though the number of questions recorded was slightly lower than in the first class. One teacher encouraged students to ask questions, one of only two schools where students asked any; in the other five schools, students asked none.

In School M, the teacher asked as many as 71 questions in session. When examining closely, we found that a field team member inadvertently informed the principal (who informed the teacher) that the purpose was to compare teaching in School M with an intervention school. The teacher appeared to try hard to make the class interactive by asking a question on almost every line of the textbook and having students answer from the text. Given School M's exceptional post-test performance, it is possible the teacher also made efforts outside researchers' presence to teach for the test, since the pre-test was accessible.

Six of seven teachers drew diagrams, usually of Earth orbiting the Sun or the solar system, though most were faintly or casually drawn and not used effectively. Four teachers used metaphorical gestures to show position or motion of celestial objects. Three teachers used analogies or examples to contextualize content, such as local star names or connecting moon phases to festivals. None used any model, with one exception: a teacher used a tiffin box lid as a model of Earth. Only one teacher used a role-play, inviting students to enact the Sun-Moon-Earth system, though the movements appeared complex and students found it funny.

7.2.2. Classroom Interactions and Participation in Intervention Schools

At the start of the module, observations in the intervention schools showed that teachers were hesitant to conduct role plays, ask open-ended questions, or invite students to the board to draw their ideas. Early lessons were largely teacher-directed, with few embodied activities, little visible collaboration among students, and mistakes typically corrected quickly rather than explored. As the module progressed and teachers received workshop-based preparation and in-school support, they began to enact more of the intended embodied and interactive pedagogy. Lessons increasingly included role plays of Earth–Moon–Sun motions, teacher and student-generated diagrams on the board, and guided use of gestures to represent rotation, revolution, and tilted axes. Students responded positively. They participated enthusiastically in role plays, created spontaneous gestures to explain ideas such as inclined orbits, and came to the board to draw their own diagrams, including students who were usually quiet in regular lessons.

Classroom notes indicate that, over time, teachers became more confident in facilitating these activities and in eliciting students' reasoning. In several lessons, students' questions and partial explanations triggered further discussion rather than being dismissed, and in some cases teachers accepted corrections offered by students during role plays or diagram work. These shifts were accompanied by visible "aha" moments for both teachers and students. One teacher (from School A) described her own experience of such moments and the conceptual change she observed in her students:

> *"I have had so many aha moments. I did not expect that my children would respond so well. They responded so well…*
>
> *Now, for instance, when the children showed a little interest, I felt that now we can go deeper and explain more to the children, and see whether they are understanding or not. Earlier, they had drawn everything inside the Earth. They had drawn all those diagrams and had placed a human being inside the Earth. Then later, they realized that we do not live inside the Earth but on the Earth."*

This account illustrates the kind of reflective discussion that the module aimed to foster. The teacher's comment that she "did not expect" such a response suggests that the pedagogy challenged her prior assumptions about students' engagement and capabilities. Her description of students moving from drawing human beings inside the Earth to realising that we live on its surface captures a concrete conceptual shift that emerged through the embodied and diagrammatic activities. It also shows how the teacher used the students' initial diagrams as a starting point for deeper exploration rather than simply correcting them.

The use of local terms along with Hindi terms for scientific ideas also lowered linguistic barriers and enabled students who were less comfortable with English or formal textbook language (Hindi) to participate more fully in whole-class and small-group talk. In contrast, observations in non-intervention schools showed astronomy lessons dominated by textbook reading and factual recall questions, often answered in chorus. Across the non-intervention classrooms, collaboration, student-generated diagrams, extended use of models, and systematic engagement with students' mistakes were rarely observed. Taken together, these patterns indicate that, relative to typical practice in similar schools, the module supported a shift in intervention classrooms toward more interactive, student-centred forms of participation.

7.2.3. Digital Lessons and Student Agency

The digital lessons were designed for pairs of students to work directly at computers, explore animations and AstRoamer games, and receive immediate feedback on their choices

while discussing strategies with their peers. In practice, teachers were initially unsure about facilitating these sessions and often relied on project staff to set up the lab, troubleshoot technical issues, and guide students through the activities. Observation notes showed that during lab sessions, the facilitator had to remain continuously active. Facilitators had to help students log in, interpret feedback, connect the digital tasks to prior classroom activities, and ensure that both partners in each pair took turns responding. Managing up to ten pairs working at different places in small, noisy labs was demanding and did not reduce teacher workload. Rather, it required new skills in operating and facilitating technology resources, and in managing the computer laboratory as a learning space.

At the same time, the digital lessons marked a clear shift in classroom norms and in the distribution of agency. Students navigated the games at their own pace, tried, failed, retried, and often wanted to remain in the lab until they achieved the highest "medal" in the AstRoamer game. In several intervention schools, observation notes documented collaboration during these sessions. Students actively asked one another for help, explained how to play the game to peers who initially used trial-and-error strategies, and some students who had mastered the game began to act as informal mentors, moving between terminals to assist classmates. For students in these government schools, who rarely have hands-on access to computers or simulations, these sessions offered one of the few opportunities to operate contemporary scientific tools and manipulate visual representations similar to those used in modern astronomy. Reflecting on such experiences, a teacher in School B shared in a discussion:

> *"Teachers should have a good connection with students. Then only they answer your questions. Science and math are subjects in which activities are important. We can not just give information. That way students will not understand."*

He argued that in science and mathematics "activities are important" and that "we cannot just give information" if we want students to understand, emphasizing the need to check regularly whether students are following. These observations suggest that, despite the additional effort required, the digital lessons redistributed control over pace, tools, and strategies toward students, and contributed to a more student-centred classroom culture than that seen in non-intervention schools, where digital technology was not used and lessons remained largely textbook- and teacher-driven.

8. Discussion

The findings demonstrate that in comparison to the chalk-and-talk approach, a carefully designed embodied digital module can significantly improve astronomy learning outcomes in under-resourced government schools, even when implemented within the constraints of rural Indian classrooms. While the intervention group showed statistically significant gains in content knowledge and attitudes compared with the non-intervention group, with the latter showing no improvement or a slight decline, the average post-test score of 47 percent also reveals the limits of a short-term intervention. This partial success underscores that providing access to new pedagogies and tools, while necessary, is not sufficient for achieving equitable astronomy education; systemic constraints on teacher learning, infrastructure, and sustained support continue to shape how far such access translates into deep understanding (Kozma & Vota, 2014; Lewin, 2007).

Compared with the traditional chalk-and-talk approach, the module's embodied activities, local-language materials, and culturally grounded examples (such as festivals and indigenous astronomical terms) created more inclusive entry points into astronomy for students in multilingual, low-income government schools where home languages and everyday experiences are often marginalized. Buddy work at computers and group role-plays

meant that participation was not limited to the most fluent or confident students, but was distributed more widely across the class. Equity-oriented interventions therefore need to invest in teacher learning and support, not just in student materials (Anderson & Helms, 2001; Kozma & Vota, 2014).

8.1. Embodied–Digital Integration as a Strategy for Equitable Astronomy Education

The deliberate integration of embodied and digital approaches can function as a concrete strategy for making astronomy education more equitable (compared with the chalk-and-talk approach) in government school settings. The module's design aligned role-plays, gestures, concrete models, diagrams, animations, and games so that students encountered the same concepts through multiple, mutually reinforcing representations (Padalkar & Ramadas, 2010). This multimodal design provided students with hands-on experience with visual and interactive tools central to contemporary astronomy but are rarely available in their schools. In this sense, the intervention did not simply add technology, but broadened students' epistemic access to the ways of seeing and reasoning that characterize modern science (Sanchez & Wiley, 2017).

8.2. Engaging All Learners in Resource-Constrained, Multilingual Classrooms

The study also illustrates how embodied–digital designs, compared with the chalk-and-talk approach, can support more inclusive engagement in resource-constrained, multilingual classrooms. Embodied activities allowed students to participate using gestures, movement, and drawing, which reduced reliance on formal academic language and made it easier for students who were less confident in Standard Hindi to contribute. Local-language materials and the use of indigenous astronomical terms and festival contexts connected school astronomy to students' everyday experiences and cultural knowledge, validating these as legitimate resources for learning (Gali, 2021). In the computer lab, the buddy-login system and games structured for two-player interaction turned the scarcity of computers into an opportunity for collaborative learning, with pairs of students reasoning together and jointly making decisions (Cress et al., 2021; Hmelo-Silver & Jeong, 2021).

8.3. Teacher Education for Equitable Science Teaching

The project underscores that teacher education is central to any attempt to advance equitable science education in government schools. The teachers' initial alternative conceptions in astronomy, their reservations about interactive pedagogy, and their heavy workloads all shaped what was feasible in the classroom (Arslan & Durikan, 2016; Taşcan & Ünal, 2016). Working with teachers through the same embodied–digital module, providing detailed handbooks and demonstration videos, and offering sustained in-school mentoring were necessary to support them in enacting the intended pedagogy (Mouza, 2002; Xu et al., 2020). Crucially, seeing their own students engage enthusiastically and learn through these activities helped teachers question assumptions about what students in government schools can do (Sarangapani et al., 2021).

From an equity perspective, this level of support should not be viewed as an optional extra but as an essential condition for enabling teachers in government schools to adopt pedagogies that are routinely expected, and often better supported, in more privileged institutions (Kozma & Vota, 2014; Valanides & Angeli, 2008). The experience also challenges common policy narratives that assume technology will automatically facilitate teaching and reduce teachers' workload (Stahl, 2009; Xu et al., 2020). Instead, it shows that technology-rich, student-centred lessons require teachers to develop new skills and invest significant time and energy to use these tools effectively, making meaningful technology integration labor-intensive rather than labor-saving (Koschmann, 1996; Stahl, 2023). Equity-oriented

interventions therefore need to invest in teacher learning and support, not just in student materials (Anderson & Helms, 2001; Kozma & Vota, 2014).

8.4. Implications for Policy, Curriculum, and Future Research

Although the present intervention was implemented in a resource-constrained context, its underlying mechanisms, such as active learning, multimodal engagement, and embodied activities to support visuospatial reasoning, are universally applicable. Consequently, we argue that this module should be considered a scalable best practice for enhancing conceptual understanding and interest in science across diverse educational settings, while simultaneously serving as an equity-oriented tool to bridge opportunity gaps in under-resourced schools.

Several implications follow for policy, curriculum, and future research. For policy-makers and system leaders, the study suggests that calls for activity-based and technology-enabled science teaching in government schools must be backed by concrete provisions for local-language materials, robust infrastructure, and ongoing pedagogical and technical support (Kozma, 2005; Wagner et al., 2005). Without these, aspirations for equitable, engaging science education will remain unevenly realized across school types (Lewin, 2007). For curriculum designers, the work shows that resource constraints such as large classes and limited computers can be treated as design parameters that invite collaborative and embodied solutions and laboratory activities (Cress et al., 2021; Hmelo-Silver & Jeong, 2021).

The study highlights the importance of context-specific design and multi-layered support. Lightweight offline digital resources, local servers, and close collaboration with state agencies and school leadership were essential in this case (Kozma & Vota, 2014; Mulla & Nagarjuna, 2022). Recent evidence from rural India shows that while smartphone access has expanded dramatically, simply providing devices does not guarantee meaningful learning benefits, but teacher support, context-specific resources, and structured opportunities to use technology for learning are essential (ASER Centre, 2024) Similar initiatives will need to map the factors that affect implementation in their own contexts and build in mechanisms for logistical problem-solving and teacher support (Mouza, 2002; Valanides & Angeli, 2008). Finally, the study raises questions for future research about how to maintain flexibility in design and provide extensive support while scaling, and how longer-term, cross-topic work might engage more deeply with students' and teachers' belief systems. Addressing these questions is crucial if embodied–digital approaches are to move beyond small, well-supported pilots and become part of the everyday experience of science learning for students in government schools.

9. Conclusions

This study shows that providing students in rural Hindi-medium government schools with coordinated access to embodied activities and digital visualizations can improve their understanding of astronomy concepts, especially those that demand spatial reasoning; they can help sustain their interest in science (Ubben et al., 2025), although average achievement levels remained modest and deeply held beliefs about celestial influence changed only to a limited extent (Galano et al., 2018; Subramaniam & Padalkar, 2009). By integrating contemporary tools of astronomy, such as simulations and games, with low-cost embodied pedagogies that are feasible in resource-constrained settings, the module (in comparison to the chalk-and-talk approach) broadened students' epistemic access to the representations and practices that define modern science. The work also demonstrates that, with intensive and context-sensitive support, teachers in government schools can adopt and adapt such approaches, making classrooms more interactive and inclusive (Mouza, 2002; Sarangapani

et al., 2021). These findings support the view that equitable and justice-oriented science education should include equitable access not only to schooling but also to the embodied and technological tools, through which scientific knowledge is constructed and communicated (Kozma & Vota, 2014; Lelliott & Rollnick, 2010).

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Institutional Review Board Statement: This study was approved by the TISS Institutional Review Board on 13 September 2016.

Informed Consent Statement: Written permission was obtained from the Head Teachers of all participating schools. Teachers and students were informed about the purpose of the study and assured that their participation was voluntary, with the option to opt out at any time. Due to low literacy levels among parents in the study population, obtaining signed informed consent from all parents was not feasible. This approach was approved by the Institutional Review Board to ensure ethical compliance while respecting the cultural and literacy context of the community.

Data Availability Statement: Anonymized data will be provided on reasonable request. Due to the consent forms signed by the participants, we are not allowed to share raw data.

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Appendix A. Indigenous Astronomy in the Indian Context

One key function of indigenous astronomy was timekeeping. Many Indian calendars use prominent stars or *Nakshatras* (lunar mansions) visible at that time to define the month, and lunar phases to define the day; *tithi* (literally, the date) indicates both. Festivals are scheduled according to lunar phases, a practice shared by major Indian religions—Hinduism, Buddhism, Jainism, Sikhism, and Islam. The moon passes through one *Nakshatra* each day, so there are 27 of them; the sun and planets also transit them. *Nakshatras* mark seasonal changes as well. For example, when the sun appears to enter the *Mrigashirsha Nakshatra* (i.e., when the *Mrigashirsha* constellation is behind the sun) coincides with the onset of the monsoon. Commonplace Indian calendars combine such indigenous information with Gregorian calendars. For more information on Indian astronomy, see Bag (2015).

Appendix B

Basic Astronomy

Pre-Test (correct responses are in boldface for readers' convenience)

A. Indicate whether the following sentences are true or false

1. Every day at noon, the Sun is exactly overhead.

T **F**

2. The Moon does not rotate around its own axis.

T **F**

3. Saturn can be seen by the naked eye (without a telescope).

T F

4. Planets which are closer to the Sun take more time to complete one revolution than the planets which are farther away from the Sun.

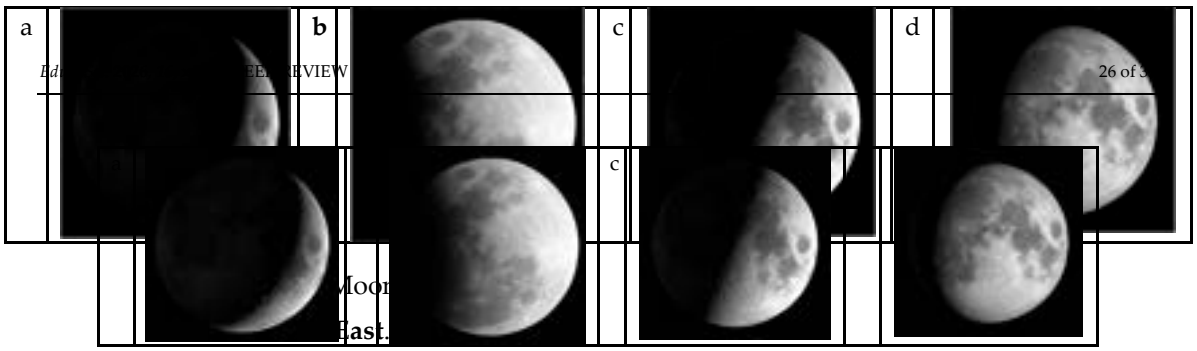
T **F**

5. Eclipses are bad omens and should not be seen.

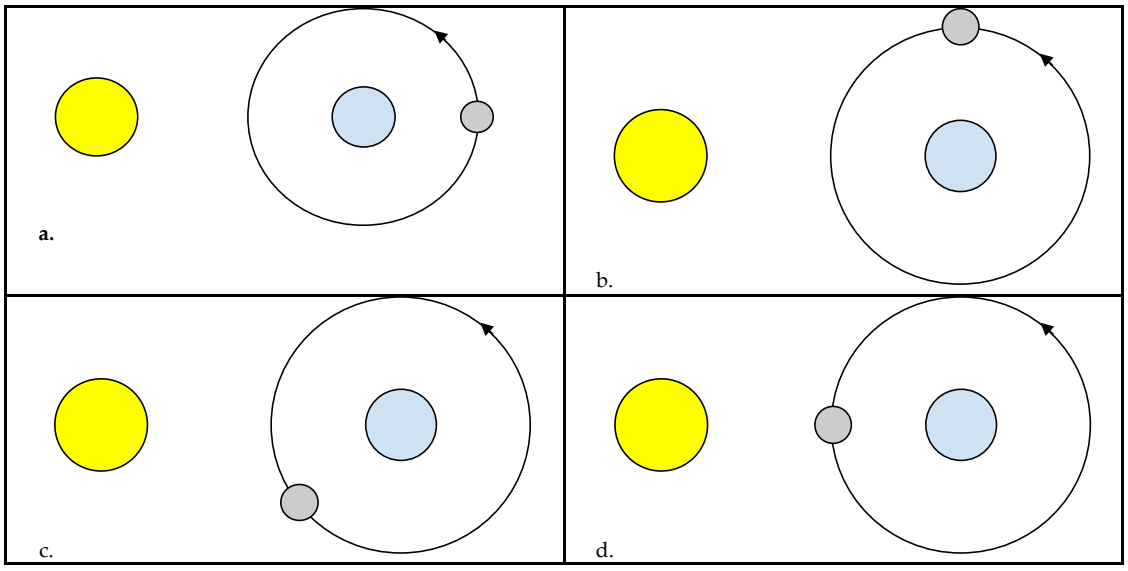
T **F**

B. Choose the correct option

1. Day and night occur because:
   - **a.** The Sun moves around the Earth.
   - **b.** The Earth revolves around the Sun.
   - **c.** **The Earth rotates around its own axis.**
   - **d.** The Earth's axis is tilted.
2. Seasons occur on the Earth because:
   - **a.** The Sun is closer to the Earth in summer than in winter.
   - **b.** The Earth's orbit is elliptical.
   - **c.** **The Earth's axis is tilted.**
   - **d.** The Earth rotates around itself.
3. Which of these pictures is NOT a phase of the Moon?



4. The Moon rises from:
   - **a.** **East.**
   - **b.** West.
   - **c.** North.
   - **d.** South.
5. Mark the picture which shows the position of the Sun, Earth, and Moon at full moon.



6. **Which force is responsible for the Moon to revolve around the Earth?**
   - **a.** Tidal force
   - **b.** Magnetic force
   - **c.** **Gravitational force**
   - **d.** Nuclear force
7. The period from New Moon to Full Moon is called:

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6. **Which force is responsible for the Moon to revolve around the Earth?**
   - **a.** Tidal force
   - **b.** Magnetic force
   - **c.** **Gravitational force**
   - **d.** Nuclear force
7. The period from New Moon to Full Moon is called:
   - **a.** ***Shukla Paksh***
   - **b.** *Pitru Paksha*
   - **c.** *Krishna Paksha*
   - **d.** *Uttarayan*
8. In what phase is the Moon on Diwali night?
   - **a.** Full Moon
   - **b.** Crescent
   - **c.** Gibbous
   - **d.** **New Moon**
9. Which is the brightest star in the night sky?
   - **a.** Pole Star
   - **b.** Venus
   - **c.** Moon
   - **d.** **Sirius**
10. The asteroid belt is situated between:
   - **a.** Earth and Mars.
   - **b.** **Mars and Jupiter.**
   - **c.** Jupiter and Saturn.
   - **d.** Saturn and Uranus.
11. Which is the correct order from the smallest to the largest in size?
   - **a.** Moon–Saturn–Earth–Sun
   - **b.** Saturn–Moon–Sun–Earth
   - **c.** **Moon–Earth–Saturn–Sun**
   - **d.** Earth–Moon–Sun–Saturn
12. Which is the correct order from the nearest to the farthest from the Earth?
   - **a.** Moon–Uranus–Sun–Polestar
   - **b.** Sun–Moon–Uranus–Polestar
   - **c.** Polestar–Uranus–Moon–Sun
   - **d.** **Moon–Sun–Uranus–Polestar**
13. Which of the following objects produces its own light?
   - **a.** Moon
   - **b.** Mars
   - **c.** **Star**
   - **d.** Asteroid
14. Which of the following is not part of our Solar System?
   - **a.** **Galaxy**
   - **b.** Comet
   - **c.** Satellite
   - **d.** Asteroid

15. Which of the following is the name of a *nakshatra* (lunar mansion)?
    - **a.** *Makara* (मकर)
    - **b.** ***Rohini* (रोहिणी)**
    - **c.** *Shani* (शनी)
    - **d.** *Bramhahridaya* (ब्रह्महृदय)

C. Mark how much you agree or disagree with the statements below

1. I enjoy learning science.

Strongly disagree				Strongly agree
1	2	3	4	5

2. Scientific thinking should be used in making decisions in everyday life.

Strongly disagree				Strongly agree
1	2	3	4	5

3. I find astronomy interesting

Strongly disagree				Strongly agree
1	2	3	4	5

4. I would like to continue to learn astronomy in college (after 10th grade).

Strongly disagree				Strongly agree
1	2	3	4	5

5. Planets can influence our lives in a supernatural way

Strongly disagree				Strongly agree
1	2	3	4	5

D. Please select options with which you agree (you can choose multiple options)

In the future, I would like to engage in

- a. Observations of the Moon, Sun, stars and other astronomical objects
- b. Learn more about different theories such as the formation of stars and the solar system
- c. Drawing pictures and making films about astronomy
- d. Preparing telescopes, satellites and other instruments
- e. Horoscopes and astrology
- f. Doing calculations of orbits, energy, etc.
- g. Studying how astronomy was developed in different parts of the world
- h. Not interested in astronomy

E. Draw a picture of the Earth. Show the following things and label them:

- a. Axis of Earth's rotation
- b. North Pole
- c. South Pole
- d. Equator
- e. Draw small human beings standing on the Earth (to show where they live on the Earth) as you might see them from a spaceship

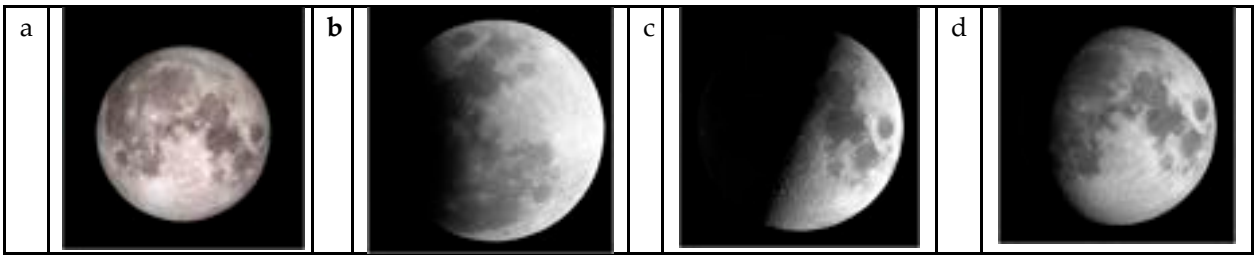
Basic Astronomy
Post Test
(Maximum possible marks: 30)

A. Indicate whether the following sentences are true or false

1. Every day at noon, the Sun is exactly overhead.
   T **F**
2. The Moon does not rotate around its own axis.
   T **F**
3. Mars can be seen by the naked eye.
   T F
4. Planets which are closer to the Sun take less time to complete one revolution than the planets which are farther away from the Sun.
   T F
5. The Sun is at the centre of our Milky Way.
   T **F**
6. If you make a wish while watching a shooting star, it comes true.
   T **F**

B. Choose the correct option

1. The Sun appears to move from East to West because
   - **a.** The Earth revolves around the Sun.
   - **b.** **The Earth rotates around its own axis from West to East.**
   - **c.** The Earth rotates around its own axis from East to West
   - **d.** The Sun moves around the Earth.
2. Imagine that the Earth's orbit was changed to be a perfect circle about the Sun so that the distance to the Sun never changed. How would this affect the seasons?
   - **a.** We would no longer experience a difference between the seasons.
   - **b.** We would still experience seasons, but the difference would be much LESS noticeable.
   - **c.** **We would continue to experience seasons in the same way we do now.**
   - **d.** We would experience seasons with the difference MORE noticeable.
3. Which of these pictures is the Moon during the eclipse?



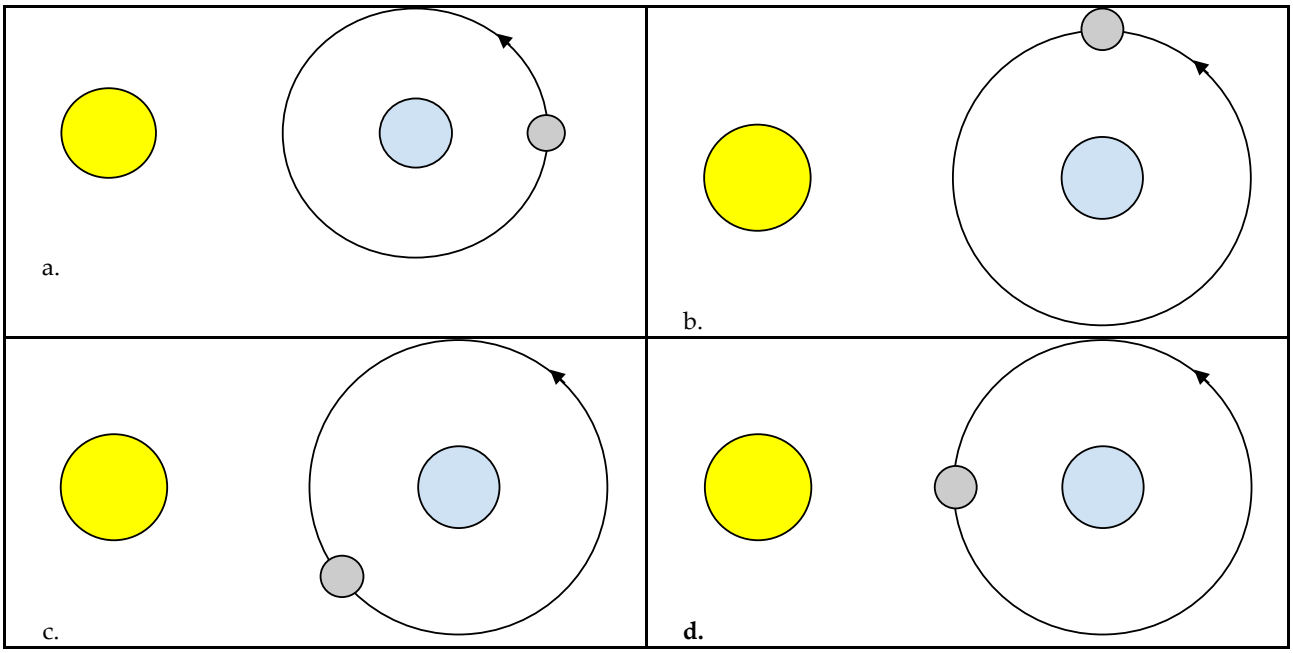
4. The Moon sets at:
   - a. East.
   - b. **West**.
   - c. North.
   - d. South.

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4. The Moon sets at:
   a. East.
   b. **West**.
   c. North.
   d. South.

5. Mark the picture which shows the position of the Sun, Earth and Moon at the new moon.

5. Mark the picture which shows the position of the Sun, Earth and Moon at the new moon.



6. Which force is responsible for the Earth to revolve around the Sun?
   a. Tidal force
   b. Magnetic force
   c. **Gravitational force**
   d. Nuclear force

6. Which force is responsible for the Earth to revolve around the Sun?
a. Tidal force
b. Magnetic force
c. **Gravitational force**
d. Nuclear force

7. The period from Full Moon to New Moon is called:
   a. *Shukla Paksha*
   b. *Pitra Paksha*
   c. ***Krishna Paksha***
   d. *Uttarayan*

7. The period from Full Moon to New Moon is called:
a. *Shukla Paksha*
b. *Pitra Paksha*
c. ***Krishna Paksha***
d. *Uttarayan*

8. Which phase of the moon signifies Eid? Choose the correct option
   a. Full moon
   b. **Crescent**
   c. Gibbous
   d. New Moon

8. Which phase of the moon signifies Eid? Choose the correct option
a. Full moon
b. **Crescent**
c. Gibbous
d. New Moon

9. Which is the brightest star in the night sky?
   a. Pole Star
   b. Venus
   c. Moon
   d. **Sirius**

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10. The asteroid belt is situated between:
    a. Earth and Mars.
    b. **Mars and Jupiter.**
    c. Jupiter and Saturn.
    d. Saturn and Uranus.

11. Which is the correct order from the smallest to the largest in size?
    a. Moon–Saturn–Earth–Sun

b. Saturn–Moon–Sun–Earth
c. **Moon–Earth–Saturn–Sun**
d. Earth–Moon–Sun–Saturn

12. Which is the correct order from the nearest to the farthest from the Earth?
a. Moon–Uranus–Sun–Polestar
b. Sun–Moon–Uranus–Polestar
c. Polestar–Uranus–Moon–Sun
d. **Moon–Sun–Uranus–Polestar**

13. Which of the following objects produces its own light?
a. Moon
b. Mars
c. **Star**
d. Asteroid

14. Which of the following is not part of our Solar System?
a. **Galaxy**
b. Comet
c. Satellite
d. Asteroid

15. Which of the following is the name of a *nakshatra* (lunar mansion)?
a. *Karka* (कर्क)
b. ***Krittika* (कृत्तिका)**
c. *Mangal* (मंगल)
d. *Agastya* (अगस्त्य)

16. Suppose a lunar eclipse can be seen from the Earth. What would be seen from the Moon at the same time?
a. **The Solar eclipse**
b. The fully lit Earth
c. Half-lit Earth
d. The Lunar eclipse

17. Transit of the Mars will be visible from
a. Mercury
b. Venus
c. Earth
d. **Jupiter**

18. A planet has a solid surface, is the hottest in the solar system and rotates from East to West. Which planet would it be?
a. Mercury
b. **Venus**
c. Mars
d. Ceres

19. The Sun mostly consists of
a. Oxygen
b. Sodium
c. **Hydrogen**
d. Gold

Questions C, D and E remain the same as the pre-test, hence have not been repeated here.

Note

[1] The CLIx platform allowed for two students to login on one computer simultaneously. The platform recorded these two logins as buddies.

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