

Article

Modeling with Embodiment for Inquiry-Based Science Education

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Abstract

Modeling is a fundamental scientific procedure for understanding nature, and it is also one of the basic strategies in inquiry-based science education. Among the various tools available for modeling, this article focuses on investigating a particular framework that uses embodiment to understand both macroscopic and microscopic phenomena. Within this approach, students actively engage as agents in the model and together build the final representation. For that, we present a specific methodology (the IBME approach) for inquiry-based modeling with embodiment. We specify the steps of the modeling approach, which were subsequently tested through instructional sequences based on this method with second-year students obtaining a degree in Primary Education at a public university. We analyzed the instructional sequences both quantitatively and descriptively. The quantitative analysis compares the results of an experimental group ($n = 86$) with a control group ($n = 68$) that does not work with inquiry-based modeling. Both groups address the same concepts, and at the end, they complete a questionnaire. The descriptive analysis discusses the details of the modeling process and the discussions that take place throughout the teaching sequences; on the other hand, it also summarizes the progress in the modeling process based on three qualitative parameters. The results obtained after implementing these sequences show significant differences compared to the control group. The descriptive analysis illustrates how students are able to reach the final model by inquiry, that is, through the discussion fostered by the modeling process itself, involving models of different levels of complexity.



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1. Theoretical Framework

Inquiry-based science teaching, or the teaching of inquiry in science, essentially involves the introduction of scientific procedures (science process skills) into the classroom (Capps & Crawford, 2013; Minner et al., 2010; Peffer et al., 2015; Vo & Simmie, 2024). The scientific procedures associated with the different stages of an investigation assume two fundamental roles (Brookes et al., 2020). On the one hand, they become part of what must be taught (procedures come to be an educational goal). On the other hand, they are the way through which students learn about a natural phenomenon.

Every inquiry process has distinct phases to approach the phenomenon and the problem to be studied (problematization, observation, speculation, and hypothesis formulation); to investigate (a methodology to test the hypothesis); and to conclude, evaluate, and communicate. However, the central phase in an inquiry process varies depending on the characteristics of the phenomenon being studied. There are different ways of conducting

research (methodologies), and, most importantly, we must distinguish between empirical inquiry and model-based inquiry (Etkina et al., 2006; Van Driel & Verloop, 2002; Windschitl et al., 2008). We can conduct empirical inquiry when the phenomenon is directly manipulable, and an experimental design can be proposed to be carried out in the classroom or laboratory. But, if the phenomenon cannot be directly manipulated because it is far from the human scale, such as in the case of some macroscopic phenomena (e.g., the study of the Moon, planets, or astronomy in general) or microscopic phenomena (e.g., atoms, molecules, etc.), we then turn to the process of modeling (Van Der Valk et al., 2007). Such models at the astronomical, molecular, or atomic level pose great difficulties for students (Palomar & Solbes, 2015; Tuzón & Solbes, 2016) that can be overcome by involving students in the model-building process.

Models in scientific research are used to understand complex phenomena. Models are provisional schemes or structures that correspond to real objects, situations, or types of situations, with explanatory power that helps scientists and engineers understand how things work (National Research Council, 1996). They are used as approximate, schematic, and simplified explanations that are useful to understand and build predictions about a particular phenomenon. In science education, as said before, they consist of a particular set of science process skills to be learned as part of an inquiry process. Modeling in science teaching is based on the construction, use, evaluation, and revision of scientific models and has been proven to be effective to learn about natural phenomena (Acher et al., 2007; Buty et al., 2004; Clement, 2000; Schwarz et al., 2009). Like any inquiry process, modeling has the advantage of naturally incorporating a learning situation in which students can express their prior ideas or misconceptions (Hernández et al., 2015). The process will therefore allow them to work on these ideas as they will be part of the models that they will propose and that will need to be refined.

Models take many forms, including physical objects, blueprints, mental constructs, mathematical equations, and computer simulations (National Research Council, 1996, p. 117; Oliva, 2019). An interesting tool that we aim to analyze is the use of the body to represent a natural phenomenon (Agostini & Francesconi, 2021). This is called *embodiment* (Tuzón & Solbes, 2017; Johnson-Glenberg et al., 2012; Tuzón & Solbes, 2024). Students act as atoms, stars, chemical bonds, waves, or the corresponding elements of the model to demonstrate how the phenomenon behaves (Niebert & Gropengiesser, 2015) by incorporating the phenomena into their environment and scale. This allows them to represent dynamic processes and connects them to the properties involved as they become the agents of the model. In this sense, Lindgren and Moshell (2011) have explained that students who have learned with embodiment often use elements of movement in the subsequent representation of model images.

Some authors (Amin et al., 2015) point out that cognitive processes enlist the material, symbolic, and social structures of the environment, reducing what actually needs to be realized in the mind itself, and that even the cognition that takes place in the ‘mind’ itself is based on knowledge structures that emerge from body-based experiences. Thus, embodiment appears as a successful strategy to favor learning, which has been demonstrated in fields such as linguistics, neuroscience, and psychology (Barsalou, 2008; Casado, 2017; Lakoff & Johnson, 2008; Pozo, 2017). The key lies in the physical activation of sensorimotor neurons, which seems to enable deeper learning than mere observation (Kontra et al., 2015; Johnson-Glenberg et al., 2012; Porro et al., 1996). Additionally, group interaction (with other agents) is an added value to this type of “congruent activation”, especially regarding the emergence of emergent properties.

In this article, we present a methodological framework for developing inquiry sequences based on modeling with embodiment, whether for macroscopic or microscopic

phenomena. The main question we aim to answer is the following: Can inquiry-based modeling with embodiment improve students' comprehension of natural phenomena, compared to expository teaching techniques? Given that embodiment activates sensorimotor-based cognitive processes and enhances the construction of robust mental models, we hypothesize that students engaged in embodiment-based modeling sequences will achieve significantly higher conceptual understanding than those exposed to traditional lecture-based methods. To test this hypothesis, we show the effectiveness of this methodological framework (of this approach to teaching model-based inquiry) through a quantitative evaluation of specific instructional proposals and a descriptive analysis of their implementation in class.

2. Methodology

In this section we first present the methodological approach to teach modeling with embodiment (Section 2.1). Then, in Section 2.2 we show the teaching sequences based on this approach and their evaluation with students.

2.1. Inquiry-Based Modeling with Embodiment (IBME): An Approach to Teach Science Phenomena

The framework we use is based on the modeling process presented by [Tuzón and Solbes \(2024\)](#). We refer to this as inquiry-based modeling to distinguish it from general modeling strategies, which may or may not be used within an inquiry framework. That is, modeling with students in the classroom can involve working with a pre-existing model, analyzing its properties, or, for example, teacher-directed modeling. In contrast, we present an approach in which modeling clearly occurs within an inquiry-based context where the model was deliberately built by the students themselves. Furthermore, they employed a specific tool: embodiment. Of course, this must be understood as an iterative process; usually steps B, C, and D are repeated as part of the model-building approach:

(A) Problematization and first ingredients

This step corresponds to the first phase of inquiry-based learning, as it involves first observations or clues that are going to serve students in building their model. It is important here not to give students hints about the model itself but the ingredients that they have to use to fit their proposals.

(B) Model building

This is one of the most important parts of the modeling process, which is the selection of properties that we want to include/exclude compared to the real phenomenon. With the construction of the model and its subsequent representation, the students begin the investigation phase of IBL, characterized here by the search, representation, and improvement of the model through successive iterations.

- (a) What properties do we want to represent? What objects, interactions, or variables do we want to represent? These are called included variables.
- (b) What objects, interactions, or variables are we going to exclude because they are not relevant? This is a model-building decision: an appropriate model choice that better fits the goal of my study (how far or close I want to be from the real phenomenon). These are called excluded variables by choice.
- (c) What objects, interactions, or variables are we going to exclude because they cannot be represented by my modeling tool? There will be variables that are impossible to be present in the model due to the limitations of the modeling tool. These are called excluded variables due to model limitations.

(C) Model representation

Although the entire class, which works in teams under this framework, developed their model (step B), we typically conduct a collective analysis of the representation. In this way, only one team will present their representation (role play, embodiment)

to the rest. The acting team must remain silent and should not inform the other teams about the roles they are playing or the details of the dynamics being represented: they should only perform. The other teams, while thinking about their own models, should begin making notes on step D as they observe the representation.

As we mentioned at the beginning, this is an iterative process, so it is possible that the analysis step (D) leads to another representation, performed by the same team or by a different one.

(D) Model testing

In the conclusion phase of the inquiry process, students must, after testing the model, verify its scope. To test whether the proposed model is “the good” model or still needs iteration, here are some questions that must be addressed:

- (a) Identify elements of the model and their functions: included variables.
- (b) Discuss the properties of the phenomenon that have been excluded: excluded variables by choice or by model limitations.
- (c) Reliability of the model: Does it match the observations? Is it consistent with other established models/knowledge? Our model should not contradict other models/knowledge that have already been proven.

(E) Model scope

What predictions does it provide? What are the limitations of our model? What is the related phenomenology?

These steps are formulated to be solved by the students, under the guidance of the teacher.

2.2. The Evaluation of the IBME Research Methodology

2.2.1. The Design and the Sample

To analyze the effectiveness of this embodiment-based modeling framework as an inquiry method, specific instructional sequences were developed and tested with student groups (experimental groups), as described below. The didactic sequences were evaluated in two ways: quantitatively, through a content questionnaire, the results of which are compared with a control group, and descriptively, describing the narrative thread of the discussions that unfold throughout the modeling process, in the end, summarizing the outcomes of the process through three qualitative variables.

This study targeted students in the second year of the degree in Primary Education Teaching at a public university. This degree includes a science course for teachers, covering fundamental concepts in astronomy, physics, chemistry, biology, geology, health, and sustainability. The activities of this study were conducted on various days by the researchers involved, following the syllabus provided in the subject’s teaching guide.

The quantitative analysis used a control–experimental sample contrast model. The samples consisted of 86 individuals in the experimental group and 68 in the control group. Only 12.7% of the participating students (both experimental and control groups) took science subjects in high school (15–17 years old); the rest abandoned them in the third year of secondary school (14 years old), so they have not studied science for at least 4 years. To ensure the homogeneity of both groups, they were selected based on belonging to similar enrollment groups, formed according to grades achieved in previous years. The control group covered the same concepts as those proposed in the modeling experiences for the experimental group but with a participatory lecture methodology. In these sessions, the teacher presented the concepts in an expository manner, supported by digital presentations. Although the students had the opportunity to participate in the session, embodiment experiences were not carried out in any case. The experimental group consisted of two

subgroups of students enrolled in a science course taught by two of the authors ($n = 42$ and $n = 44$).

2.2.2. The Teaching Sequences Based on IBME Methodology

Two educational interventions were prepared, designed as sequences of problematized activities based on embodiment (IBME framework). These proposals address solar system concepts (lunar phases and eclipses, apparent retrograde motion of the planets, scientific discussion of the geocentric and heliocentric models: parallax) and states of matter concepts (properties of states and changes of states).

The sequences presented here are part of broader sequences on ‘The Earth in the Universe’ and ‘The Atomic Molecular Theory of Matter’ within the subject ‘Natural Sciences for Teachers’. The modeling sequence of the systems to be embodied and the two proposed activities are specified in Table 1 for the solar system proposal and in Table 2 for the proposal on the states of matter.

Table 1. Inquiry-based sequence to discuss the solar system model.

Inquiry Problem	Step	Learning Objectives	Activity
Lunar phases: Identification and analysis.	A	Identify the phases of the Moon and the role of the Sun, Earth, and Moon in the phenomenon. Separate the lunar phases into similar phases: quarters, full, and new.	A.1 Give a brief description of the movement of the Moon around the Earth and the phases of the Moon (previous modeling data). A.2 Which way does the Earth rotate?
Representation of the full moon and new lunar phases using a model.	B, C	Identify the Sun, Earth, and Moon as elements of the model and the translation of the Moon around the Earth as a mechanism of the phenomenon. Analyze the similarities and differences between the “full and new” and “quarter” phases.	A.3 Represent the movement of the Moon around the Earth. What face of the Moon do we see? How many times has the Earth turned around itself when the Moon has made one complete revolution? A.4 Represent the phases of the full and new moon using the heliocentric model.
Discussion of the role of misalignment between the Sun, Earth, and Moon in these phases. Refinement of the model with the inclination of the lunar orbit.	D, E	Discuss and analyze why solar and lunar eclipses do not occur every “month”.	A.5 Why do eclipses not occur every month at the full and new moon phases?
Representation of the first and last quarters and discussion of the direction of rotation of the Moon around the Earth.	B, C	Find the relative position of the Sun, Earth, and Moon in the phases of waxing and waning quarters, as well as analyze the succession of the four lunar phases.	A.6 Represent the lunar phases of the waxing and waning quarters and discuss the direction of rotation of the Moon around the Earth.
Discussion about the times of day when you can see the different phases.	D, E	Highlight the diurnal visibility of the Moon and analyze the relative position of the three bodies in this situation. Analyze and compare the “fourth” phase with the new moon phase.	A.7 Discuss the times of day when the different phases can actually be seen.
Discussion of how the shape of the same phase of the Moon changes depending on latitude.	D, E	Highlight the link between astronomical knowledge and the usual geolocation. Extrapolate the knowledge acquired to situations different from the usual ones. Formulation and contrast of general hypotheses.	A.8 Could the model used in the previous activities be used for learning in schools in Australia? Analyze what the phases of the Moon would look like in the southern hemisphere.

Table 1. Cont.

Inquiry Problem	Step	Learning Objectives	Activity
Extension of phenomenology: retrogradation, parallax, and Kepler's laws.	E (A, B, C, D)	Identify the size of the solar system as one of the limitations to the representation of the model. Expand the phenomenology associated with the elements and dynamics of the solar system.	A.9 One of the main difficulties of the geocentric model was the explanation of the retrogradation of Mars by epicycles and deferents, which the heliocentric theory elegantly solved. Represent the retrograde motion of Mars using the heliocentric model. A.10 Fixed stars were used as an argument against the Copernican heliocentric theory. If the Earth moves, as Copernicus said, should we see how the position of a star on the background (the celestial sphere) varies as a matter of perspective? Represent the situation in the classroom.

Table 2. Inquiry-based sequence to discuss the matter's state model.

Inquiry Problem	Step	Learning Objectives	Activity
Macroscopic and microscopic structure of matter. Kinetic theory.	A	Enunciate the macroscopic differences between solids, liquids, and gases and propose their microscopic structure based on atomic-molecular theory and the links between particles.	A.1 Mention the macroscopic differences between solids, liquids, and gases (previous modeling data).
Microscopic structure of matter: kinetic theory.	B	Develop the model to be represented considering people as the particles that make up matter and propose the chemical bonds between them.	A.2 According to the macroscopic properties of solids, propose a microscopic representation for this state. A.3 According to the macroscopic properties of liquids, propose a microscopic representation for this state. A.4 According to the macroscopic properties of gases, propose a microscopic representation for this state.
Macroscopic properties of solids, liquids, and gases from the microscopic representation.	C, D	Understand the behavior of the particles that form matter according to the kinetic-molecular theory, the bonds that are established between them.	
Phase of matter changes.	E (B, C, D)	Understand the role of bonds between particles as a determinant of the phase of matter.	A.5. Represent a transition from solid to liquid and then to gas as the temperature increases.
Temperature as a measure of particle velocity.	E (B, C, D)	Understand the state of motion of the particles that make up matter. Understand temperature as a measure of the average kinetic energy of particles. Understand the meaning of absolute zero temperature.	

During the two sessions in which the sequences described in Tables 1 and 2 were implemented, students worked in teams of 3 to 5 members. The teacher introduced the designed activities and allowed time for discussion, intervening primarily through questions that guided the discussion and helping to summarize and conceptualize the conclusions reached by the students throughout the process. The dynamic was always the same: initial inputs, a modeling proposal from one team, collective analysis and refinement of the model, iteration with other teams, and a concluding discussion.

In contrast to the experimental group, which followed the sequences outlined in the tables according to the approach analyzed in this article, the control group addressed the same concepts but with a different approach. The control group classes followed a lecture-based methodology with a common thread: the teacher always presented the finalized model; that is, students did not participate in the process of constructing the model. For example, diagrams and images previously selected by the teacher were used to show the relative positions of the Sun, Earth, and Moon, from which the phases of the Moon were explained. To address the topic of eclipses, an image was shown depicting the inclined lunar orbit relative to the ecliptic, with the orbital nodes indicated. An animation (model) was used to demonstrate why eclipses do not occur every month. During the explanation, photographs of eclipses and diagrams were shown to explain the difference between umbra and penumbra. The phenomenon of daytime visibility was addressed using a simulation (model), an image of the Earth–Sun–Moon system, and a table showing observation times for each phase. The same simulation was used to verify the Moon’s phase from two locations in different hemispheres, and so on. In other words, as mentioned at the beginning, students worked directly with the final model or with pre-processed information.

2.2.3. Instruments for Evaluating the Effectiveness of the Didactic Sequence

To analyze the results, a quantitative and a descriptive evaluation of concepts and models was conducted. The descriptive evaluation was carried out in two ways: First, by describing the details of the discussions that occur during the modeling process. This allows for an analysis of the argumentative thread and an understanding of how the model is constructed by the students. Second, the process is summarized at the end using three qualitative variables described below. The quantitative evaluation was conducted through a questionnaire, and two opinion-based questions were proposed for the experimental group.

(1) Descriptive evaluation.

The session descriptions are presented in the Section 3. The variables used to summarize the progress of the induced modeling process are below. This could be reviewed through the recordings of the sessions.

- Achievement of the final model: Did the modeling refinement process enable students to propose the best model, in line with the learning objectives?
- Complexity of the model: How many model iterations were needed to reach the final model? It is worth noting that a higher or lower number of iterations does not necessarily indicate higher or lower effectiveness of the modeling process, as long as these iterations contribute to discussing ideas intertwined with the phenomenon. However, it does indicate the complexity of the model and the understanding of the phenomenon.
- Related submodels and misconceptions or difficulties: In most cases, the iterations occur because either the “excluded/included variables” need to be adjusted, or because a particular iteration includes a misconception that needs to be discussed. This is why we also account for the submodels that emerge and provide a summary of the difficulties that students have had to overcome.

(2) Quantitative evaluation through a questionnaire.

Both the experimental group ($n = 86$) and the control group ($n = 68$) of students answered an 8-question questionnaire on some basic concepts related to teaching sequences (see Appendix A). For validation, expert judgment and a pilot test were conducted on a group not included in the control and experimental groups. The data obtained by the four researchers were then discussed until a final consensus was reached, allowing the design of the current questionnaire. The Cronbach's Alpha test was applied, yielding a value of 0.723 for the pilot group, which was also higher than 0.7 for the experimental and control groups, indicating a medium-high reliability. The questionnaire was completed by all students one month after the last teaching intervention, without prior warning, to assess real learning.

Questions 1 to 3 refer to some of the concepts related to the modeling experiences of the Solar System (see Appendix A):

- Lunar phases and eclipses.
- Apparent retrograde motion of the planets.
- Discussion of the geocentric and heliocentric models.

Questions 4 to 7 deal with some of the concepts related to the experiences of modeling the states of matter:

- Properties of states.
- Changes of state.

All these questions were scored on a scale of 0, 0.5, or 1, according to correction criteria that assess the accuracy of the answer. Further examples of the type of answer considered correct can be seen in the analysis of answers.

According to Lindgren and Moshell (2011), students who learned with embodied activities tend to use more movement elements in their answer illustrations. The questionnaires were also analyzed to compare the number of answers with movement details (lines for orbits, arrows, etc.) between the control and the experimental groups.

The experimental group had an additional question with two items at the end of the questionnaire, regarding their impression of working with embodiment and its effectiveness in a primary school classroom (Wallon & Lindgren, 2017).

3. Results

3.1. Descriptive Evaluation

The results of embodiment can be considered very positive. The analysis shows that students acquire modeling skills in their inquiry process and follow the established steps. The discussions involved in the model-building process are deep and enable students to refine their preliminary models, as can be seen below in each of the proposed activities.

3.1.1. Proposal for the Earth–Sun–Moon System

The following are the proposed activities along with comments on how the resolution was carried out by the groups. Although the activities are numbered consecutively, it is important to note that they are not the only activities in the didactic sequence; they correspond to the concepts we intended to address through embodiment.

Lunar Phases and Eclipses

The embodiment activities on the Moon are preceded by a discussion about previous ideas regarding the Moon's position, period, and shape to approach the phenomenon and the problem to be studied. This ensures that students are familiar with the phenomena that the model aims to explain (Activity A.1, see Table 1). In this activity, one pupil represents

the Earth, another the Moon, and a third the Sun. The pupil–Moon orbits the pupil–Earth, with some groups leaving the Earth at rest, while others make it rotate around itself, though uncertain about the direction of rotation and the relationship between the Earth’s rotation and the Moon’s translation. To address this, they are given Activity A.2. In this activity, the Earth is made to rotate around itself, but the rotation periods of the Earth and the Moon are not adjusted.

During the activity, students are prompted to reflect that, when the pupil–Earth faces the Sun, their front is South, making their left side East (in contrast to defining the cardinal points when they face North). As a result, when asked how the pupil–Earth should turn for the Sun to rise in the East, they conclude that it must turn to the left, i.e., in a counterclockwise direction. The Moon also rotates around itself and orbits the Earth in a counterclockwise direction, as observed when analyzing its phases. Sometimes, it rotates in the opposite direction, and the correct direction is either reminded to the students or marked with chalk on the ground.

In Activity A.3, the pupil–Moon starts walking forward in a counterclockwise direction, always facing the pupil–Earth (alternatively, she could have walked forward and shown her left side to the Earth). Interestingly, this representation is actually correct, even if performed unconsciously, because the Moon always presents the same face to the Earth during its rotation. At this point, students are asked about the period of rotation and translation of the Moon. They know the translation period is 28 days but are not aware that the Moon rotates around itself. They repeat the movement slowly, using 0° as the position when the Sun, Moon, and Earth (in that order) are aligned, and then stop at 90° , 180° , 270° , and 360° . They realize that the Moon has rotated around itself while orbiting the Earth, resulting in both periods coinciding and being 28 days.

Once the Moon has been positioned at different angles, the next problem addressed is that of its phases (Activity A.4). The positions where the Moon is at 0° and 180° with respect to the line defined by the Earth and the Sun are referred to. Continuing from the previous activity, at 0° degrees, students notice that the pupil–Moon’s back is illuminated, indicating a new Moon. Then, at 180° , it is a full moon because the pupil’s face is fully illuminated. Activity A.5 is prompted by the previous embodiment when students ask why the Moon is not eclipsed in every new phase. In this activity, when the Moon is new, it should cover the Sun, suggesting a monthly eclipse. However, since this does not occur, when asked to model it, the Moon ducks, indicating that the plane of rotation of the Moon around the Earth is different from the plane of rotation of the Earth around the Sun, forming an angle (Figure 1).



Figure 1. Students representing the Earth–Sun–Moon system and differentiating solar eclipse from the new moon.

(A.6). At 90° , students have doubts. They think that, as they are approaching the full moon, it should appear as a crescent. However, they encounter a problem regarding the direction of the Moon's rotation. If the Moon rotates counterclockwise, they realize that the illuminated part of the Moon visible from Earth is on the right side, forming a "D" shape, which corresponds to the crescent in the northern hemisphere. Since this observation aligns with what is expected, it confirms the counter-clockwise rotation of the Moon. On the other hand, if the Moon were to rotate clockwise, they would observe the illuminated part on the left side, forming a "C" shape, which corresponds to the waning quarter in the northern hemisphere, and from waning it would become full, which is absurd.

(A.7). When the student playing the Earth faces the Sun, its highest point or zenith (which is in the South) is at 12 o'clock on Earth. When they see the Sun from the right side, it is approximately 6 o'clock, and the Sun is setting in the West. When the student turns their back to the Sun, it is 0 o'clock. Glancing off to the left, it is approximately 6 o'clock, and the Sun is rising in the East. It is important to note that the observer (pupil–Earth) is facing South to see the Sun, and there is, therefore, no contradiction with the cardinal points, which are determined by facing North. In the southern hemisphere, the Sun rises in the East and sets in the West but reaches its zenith (at 12 noon) in the North.

The Moon is then included in the form of a pupil representing it. The new moon (0°) is "seen" from 6 a.m. to 6 p.m., being at its zenith in the South at 12 noon. The waxing moon is "seen" from 12 h to 24 h, being at its zenith at 18 h. The full moon is "seen" from 18 h to 6 h, being at its zenith at 24 h, and the waning Moon is "seen" from 24 h to 12 h, being at its zenith at 18 h.

(A.8). This would be equivalent to the observer on Earth being upside down. Then at 90° , on a waxing moon, the observer would see the left side of the Moon illuminated, forming a "C" shape. At 270° , on a waning moon, the observer would see the right side of the Moon illuminated, forming a "D" shape, realizing that the opposite is true in the southern hemisphere as in the northern hemisphere.

Apparent Retrograde Motion of the Planets (A.9)

One person plays the role of the Sun, while two others play the planets, Earth, and Mars, rotating in circles around it. As for the limitations, in addition to addressing the problem of scale, they are asked what needs to happen for the Earth to observe Mars moving backward, explaining retrogradation. This leads them, in the second iteration, to refine the model by making the Earth move faster, allowing it to overtake Mars and create the appearance of backward motion (Figure 2).

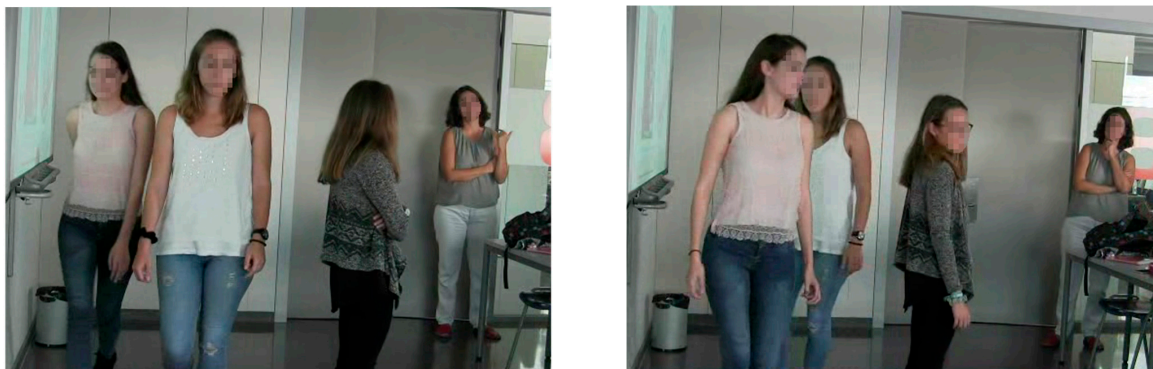


Figure 2. The students take on the roles of Mars and Earth, orbiting around another student who represents the Sun.

Discussion Between the Geocentric and the Heliocentric Model: Parallax (A.10)

Three people are needed to represent the Sun, the Earth, and a star, although some groups use two people to represent the stars. The Earth revolves around the Sun, with the star not too far away due to the limited dimensions of the usual classrooms. The student playing the Earth is asked to describe what they observe at opposite ends of the orbit, and they confirm that the star appears to move on the wall at the back of the classroom.

When questioned about how to reduce this displacement, the student adjusts the Earth's orbit to make it smaller and moves the star as far away as possible, effectively reducing the parallax.

To ensure all students can experience the phenomenon, not just those who have performed the embodiment, they are asked to place their index finger very close to their eyes and alternately wink. Then, they are asked to move their finger as far away from their eyes as possible (the whole length of their arm) and repeat the process. It is evident that, in the second case, the displacement in the background is much smaller.

Summary of the Descriptive Results for Macroscopic Phenomena

Below, we present a summary table (Table 3) that synthesizes the level of effectiveness qualitatively of the modeling as a key component of the inquiry process, according to the indicated categories: 'Effectiveness' is understood here as the extent to which the modeling process led to the construction of a final model that adequately explains the phenomenon, including the resolution of difficulties, the number of iterations required, and the integration of relevant submodels.

Table 3. Level of effectiveness of the modeling process. Moon phases.

Model	Achievement of the Final Model	Iterations	Related Submodel
Lunar phases and eclipses	Completed through the modeling process. Found difficulties: distances between celestial bodies. Relative rotational periods.	2	Rotation and translation of the Earth and the Moon and their periods, determining the relevance of the models regarding the phenomenon (selection of variables)
		2	Difficulty in distinguishing between the movements of rotation and translation to show the same face of the Moon
		3	Discussions about the alignment between celestial bodies to describe lunar phases and solar and lunar eclipses
		1	Correlation between the times of day when phases are "seen" and the north–south hemisphere difference
Apparent retrograde motion of the planets	Completed through the modeling process.	1	Differentiating the relevance of the rotation and translation of the planets regarding the phenomenon under study
		1	Discussion about the speed and scale of the model
		1	Determining the point of view on a planet and verbally describing the trajectories of other planets
Parallax	Completed through the modeling process. Found difficulties: distance between Earth and stars and Earth orbit eccentricity.	3	Problem setting and relative scales to accurately represent distances
		1	Translation movement of a planet relative to fixed stars and approximation of parallax according to the planet's point of view

3.1.2. Proposal for the States of Matter

Properties of the States of Matter

(A.1, see Table 2) The groups mention the three usual states of matter: solid, liquid, and gas, along with their macroscopic properties. Solids do not change shape or volume when transferred from one container to another; liquids do not change volume but adapt to the shape of the container holding them, and gases occupy the entire volume of their container. Other states, such as plasma, Bose–Einstein condensates, Fermi condensates, etc., are not mentioned.

In Activity A.2, two or more groups participate. Eight or nine students are asked to come to the board and represent a solid. The initial groups are positioned closely together in a huddle. Some students hug each other to indicate bonds, which aids the next step. They are reminded of how atoms are arranged, for example, in salt, highlighting that they are ordered and bonded. They then attempt to arrange themselves in neat rows, but the bonding is not quite accurate, as they bond with the student in front but not with the one next to them or vice versa. Suggesting that they put their hand on the shoulder of the student in front and the one on the right helps them form a more faithful model of the structure of a solid. However, they still miss one detail—the state of vibration. When asked if all the particles are at absolute rest, the participants hesitate and soon realize that they must be vibrating around their equilibrium position.

Having made the solid model in the previous activity, it becomes easier for them to understand that the bonds weaken (they move away from each other) but do not disappear (they keep their hands clasped, but without forming a solid) in Activity A.3.

Building on the evolution of the previous two activities, in Activity A.4, the participants in the groups separate and occupy all available space in the classroom, letting go of their hands and moving freely. All groups agree on this representation.

Changes of State

As we have already mentioned, in the solid state, the students remain ordered, bonded, and in a slight state of vibration. They can then be asked (A.5) at what temperature they would be if they were motionless, as they initially proposed in previous activities, but they do not know. It is worth remembering that atoms (or molecules) are only at rest at 0 K, which allows us to ask them what happens at other temperatures. They correctly point out that they vibrate or shake, which allows us to introduce the concept of thermal agitation.

When asked what happens with increases in temperature, they say that the atoms start to vibrate with greater amplitude (or speed) and that bonds are broken, leading to the transition to the liquid state (see Figure 3 and Table 4). Regarding the container, which is important in maintaining the shape of the liquid, it is suggested that they move closer to the wall, which is often the case in many classes due to a lack of space. If the liquid continues to heat up, the vibration (or thermal agitation) increases, and the students start to disperse around the room, embodying the change to the gaseous state.

Table 4. Level of effectiveness of the modeling process. Matter.

Model	Achievement of the Final Model	Iterations	Related Submodel
The solid state	Completed through the modeling process. Found difficulties: Representing vibrations.	2	Particle arrangement (molecules or atoms) and identification of properties with the representation (distance between them, bonds. . .)
		2	Identification of macroscopic properties (solid behavior according to temperature or container change, compression) with microscopic behavior

Table 4. *Cont.*

Model	Achievement of the Final Model	Iterations	Related Submodel
The liquid state	Completed through the modeling process.	1	Particle arrangement (molecules or atoms) and identification of properties with the representation (distance between them, bonds...)
		1	Bonding in liquids
		2	Identification of macroscopic properties (solid behavior according to temperature or container change, compression) with microscopic behavior
The gaseous state	Completed through the modeling process. Found difficulties: Simulating the full particle movement using the classroom completely.	1	Particle arrangement (molecules or atoms) and identification of properties with the representation (distance between them, bonds...)
		1	Bonding in gases and pressure
		1	Identification of macroscopic properties (solid behavior according to temperature or container change, compression) with microscopic behavior
Changes of state according to temperature	Completed through the modeling process. Found difficulties: How to model bond changes in the state change moment.	2	Combination of all the previous elements, nuances on intermediate states



Figure 3. Embodying the change from solid to liquid.

Summary of the Descriptive Results for Microscopic Phenomena

As performed with macroscopic phenomena, we present below a summary table of the qualitative modeling process.

3.2. Results of the Quantitative Evaluation Through Questionnaires

The rating of the questionnaires was obtained by assigning 0, 0.5, or 1 point depending on the accuracy of the answers, as mentioned above (Appendix B).

Statistical analysis of the results using the SPSS program (v21.0) shows that there is a statistically significant difference between the means of the experimental and control groups for certain items, as determined by the Mann–Whitney U test.

In the comparison between the control and experimental groups, the following results were obtained. For item 1.a (Moon phases), the control group had a mean score of $0.118 (\pm 0.275)$, while the experimental group reached $0.256 (\pm 0.374)$, with a significant difference ($p = 0.010$). In item 1.b (lunar eclipse), the control group's mean was $0.140 (\pm 0.257)$, compared to $0.238 (\pm 0.284)$ in the experimental group ($p = 0.017$). For item 1.c (new Moon), the control group obtained a mean of $0.074 (\pm 0.249)$, while the experimental group achieved $0.256 (\pm 0.374)$, with a significant difference ($p = 0.010$).

In item 2 (retrograde motion), the control group scored a mean of $0.044 (\pm 0.167)$, and the experimental group $0.203 (\pm 0.291)$, with a highly significant difference ($p < 0.001$). Regarding item 3 (parallax), the control group mean was $0.037 (\pm 0.248)$, and the experimental group reached $0.302 (\pm 0.257)$ ($p < 0.001$).

For item 4 (liquid state), the control group's mean was $0.058 (\pm 0.162)$, and the experimental group's was $0.169 (\pm 0.283)$ ($p = 0.008$). In item 5 (solid state), the control group scored $0.118 (\pm 0.230)$ and the experimental group $0.250 (\pm 0.304)$ ($p = 0.004$). In item 6 (gas state), the control group achieved a mean of $0.110 (\pm 0.226)$, while the experimental group reached $0.291 (\pm 0.311)$, with a significant difference ($p < 0.001$).

Finally, in item 7 (phase transitions using the model), the control group's mean was $0.154 (\pm 0.248)$ and the experimental group's $0.448 (\pm 0.317)$ ($p < 0.001$). In item 8 (limitations of the model), the control group scored $0.029 (\pm 0.118)$, and the experimental group scored $0.314 (\pm 0.368)$, also with a highly significant difference ($p < 0.001$).

As observed (Figure 4), the results of the control group are very low. As we have said in the Section 2, a low percentage of students have taken science subjects in high school, so they have not studied science for at least 4 years. The results of the experimental group show a considerable improvement compared to those of the control group, with statistically significant differences ($p < 0.05$) in all items. In the questions related to the states of matter (4–7), the results clearly improve as they progress. Students are asked about the properties of liquids, solids, and gases, and finally (question 7), they have to explain a representation of the whole. We believe that this progression could be attributed to a better understanding of the model as they respond. This effect is not observed in the control group, which suggests that embodiment plays a significant role. To assess which items had a greater effect, Cohen's d was calculated (see Table 5).

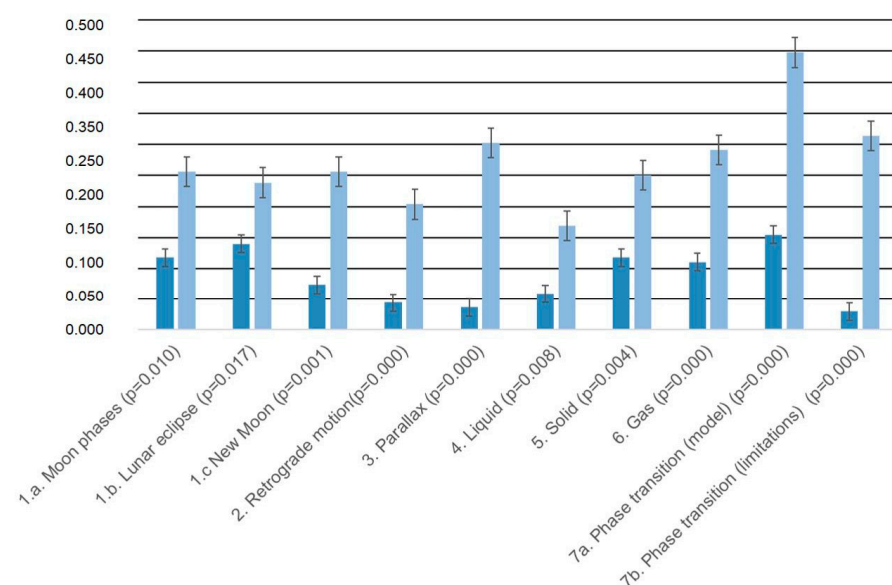


Figure 4. Comparison of the means obtained for each questionnaire item between the experimental and control groups, represented in light blue and dark blue, respectively. Note: The p -value from the mean comparison using the Mann–Whitney U test is shown, as the distributions were non-normal.

Table 5. Measuring effect size using Cohen's d.

	Cohen's d	Effect Size
1.a. Moon phases	0.43	Middle
1.b. Lunar eclipse	0.36	Small
1.c. New Moon	0.54	Middle
2. Retrograde motion	0.65	Middle
3. Parallax	1.26	Large
4. Liquid	0.46	Middle
5. Solid	0.48	Middle
6. Gas	0.65	Middle
7. Phase transition (model)	1.10	Large
8. Phase transition (limitation)	0.99	Large

As has been said before, to analyze embodied learning reflected in the use of movement elements in the illustrations (Lindgren & Moshell, 2011), we examined the students' diagrams in both the control and experimental groups for the first question (schematic representation of the Moon phases) in order to distinguish and count diagrams with movement elements drawn and without them. It has been found that 44% of the students in the experimental group had incorporated drawings with movement elements, while only 19% of the students in the control group had done so.

The inclusion of arrows and path lines provides more information in the answers as they not only reflect the elements of the model but also depict the dynamics of the represented system, in line with the achievements in the refinement of the model from the embodiment activities carried out in the classroom (see Figure 5).

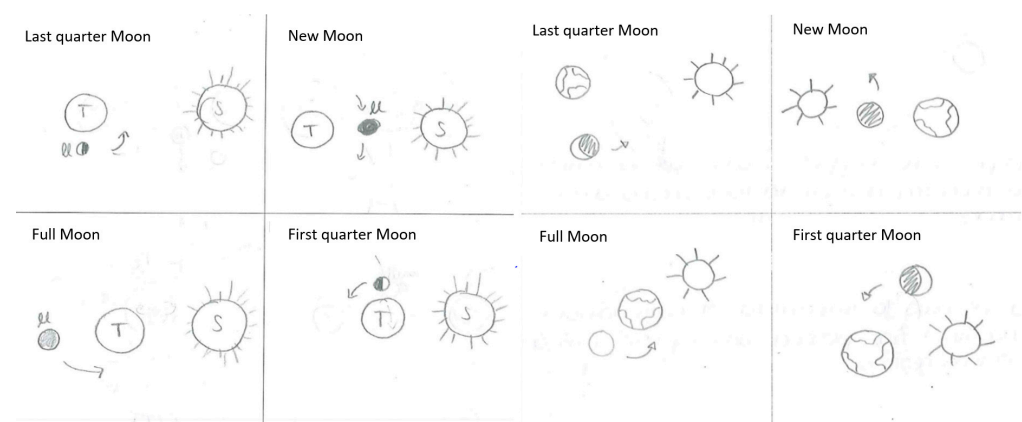


Figure 5. Examples of the response to item 1 of the questionnaire for the experimental group. Note: Earth is marked with T, the Sun with S, and the Moon with double l in the first drawing.

As an example, the wording of the responses to the questions posed can be compared between the control group and the experimental group. This allows us to assess the greater elaboration in reasoning, which, as previously explained, has been evaluated using a numerical score.

Among the questionnaire answers of the students in the experimental group, there are quite a few cases with a correct and complete explanation of why we do not have eclipses at every full moon.

“Because there is only an eclipse when they are on the same line, as the line (orbit) is inclined, it is not at the same level, and there is no eclipse.”

“Because the orbit is inclined, i.e., it is not at the same level.”

“Because they are not totally aligned, and for an eclipse to exist, they have to be aligned.”

Most of the students in the control group did not answer, and others gave a bad explanation associated with the shadow of the Earth on the Moon. Three students said that they had worked on the phenomenon in the classroom but did not remember the explanation.

Some of the answers from the experimental group give the correct explanation about the new moon with adequate argumentation:

“Because the Moon is in front of the Sun so that the side of the Moon facing the Earth is not illuminated by the Sun’s rays. Therefore, it is not illuminated from the Earth.”

“The Moon is located between the Earth and the Sun so that its illuminated hemisphere cannot be seen from our planet.”

However, similar arguments are also offered by the control group, as no statistically significant differences were found.

In the same way, students in the experimental group can correctly explain the retrogradation of Mars, but they do not find completely correct answers in the control group:

“From Earth, we can see Mars going forwards and backwards because each planet rotates at different speeds, and so at each moment, we can see Mars in a more forward or backward position.”

The same level of argumentation is found in the question about parallax in the questionnaires of the experimental group but not in those of the control group who were taught the concept through the explanation of a diagram.

“Due to the great distance between the Earth and the stars, no movement of the stars can be seen.”

With the questions on states of matter, both groups were quite good, although the level of argumentation is better in the experimental group:

“Bonds allow it (liquid) to change shape, but the volume remains the same.”

In the control group, most of the answers do not refer to the bonds between particles and do not justify the constancy in volume.

In the question about solids, the experimental group does not obtain a significant improvement despite having well-argued answers such as the following one:

“The bonds between the particles are so strong that they do not separate, therefore, the solid always maintains its shape and volume.”

Incomplete answers similar to those of the control group are also often found.

“Because the particles are very close together and move very little.”

In the gas item, the experimental group also managed to argue better with answers in the style of pointing out the bonds and the change in distance.

“Because the bonds that join the particles of gases are so weak that they allow them to both change position and increase the distance between them and therefore occupy all the space available to them.”

Finally, in both groups, the embodiment activity for the change of state is more or less well proposed.

“...as the temperature rises, they would have to move more in their place, then changing places and finally around the whole class.”

However, for the question about limitations to the model in the control group, it is argued on the basis of the available space mostly, and in the experimental group, reference is also made to elements of the modeled phenomenon: links, scale, particle positions, vibration velocity.

“They can only stand upright, although they can climb on a chair.”

“You don’t know the exact amount of temperature that rises or falls, so you don’t know the dimension to which the pupils have to expand.”

“...people don’t go as fast as particles...”

“It is difficult to represent the links.”

Similarly to what was observed in item 1.a, 60% of the students in the experimental group who included drawings in their answers to the questionnaire about matter (drawing was not required) also incorporated elements of movement. In contrast, no students in the control group used drawings or included dynamic elements in them (see Figure 6).

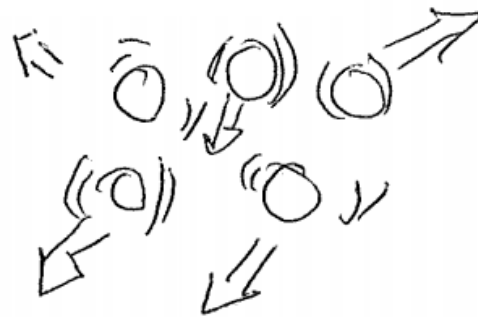


Figure 6. Example of the response to item 6 of the questionnaire. From a student of the experimental group.

3.3. Results for the Additional Question for Students in the Experimental Group

As mentioned above, the students in the experimental group answered an additional question with two items: “8. Evaluate the embodiment experience: (a) Say if you found it useful or not, if it helped you to understand the phenomenon, or any other appreciation (b) Say if you think it is applicable in a primary school classroom”.

Most of the students in the experimental group answered both opinion questions. In the answers, it is observed that almost all of them agree with the idea that embodiment is useful to remember the concepts worked on.

“There were times when I did not understand with the theoretical explanation, but with the moon cycle, I found it very useful.”

“More visual, easier to learn.”

“It helps a lot to understand, in spite of the limitations it may have to represent specific aspects.”

“It has been quite useful when it comes to remembering both astronomy and chemistry questions.”

4. Discussion

Inquiry-based learning is a methodology that has been widely researched in recent years (Pedaste et al., 2015), although there is little research on embodiment modeling. For the latter, Kolovou (2022) provides a classification, and this study would fall into the category of “direct embodiment”, where spaces and people involved are used as elements, and performance serves as active rules for the model being represented. In this line, we find two kinesthetic learning activity (KLA) works related to celestial movements: one about sunrise and sunset, the Moon, and constellations (Plummer, 2009) and another about

the retrograde motion of planets (Richards, 2012). In both cases, improvements were observed in the test results of the experimental group compared to a control group, which aligns with the results presented in our study that addresses not only retrogradation but also more complex movements like that of the Moon. The main difference between most studies framed within this “direct embodiment” approach and our proposal lies in the incorporation of inquiry as a key element in the process. That is, the model is built and discussed by the students themselves within a specific dynamic, rather than starting from a given model.

With the activities proposed in our proposal, we obtained small-to-medium effect sizes ($d = 0.36$ to $d = 0.54$) regarding the questions related to the Earth–Sun–Moon system (1a, 1b, 1c). In a physics course for future elementary school teachers, where students were used as observers simulating the Earth with a white sphere as the Moon and a light bulb as the Sun, Trundle et al. (2002) found substantial improvements in the understanding of Moon phases and lunar eclipses. In our case, question 1b was the only one that showed a small effect size with our proposal. This may be due to the fact that understanding this phenomenon requires taking into account the inclination of the Moon’s orbit relative to the ecliptic plane, which involves three-dimensional reasoning. This spatial complexity can pose a challenge for students who are more used to two-dimensional representations of the Earth–Sun–Moon system (Plummer, 2014).

Regarding the question about understanding the retrograde motion of planets (2), our research obtained a medium effect size ($d = 0.65$), slightly higher than the effect sizes obtained by Richards (2012), who found small effect sizes ($d = 0.2$ to $d = 0.35$).

For understanding parallax (question 3), we obtained a large effect size ($d = 1.26$), while Richards (2012) obtained a small effect size ($d = 0.28$) when comparing the performance between control and embodiment groups using a multiple-choice question that evaluated the definition of parallax. In experiences with virtual reality, involving students’ movement in a virtual environment, good results have also been obtained in understanding parallax (Windmiller et al., 2021). However, in an introductory astronomy course with university students, Madden et al. (2020) did not find differences comparing instruction using embodiment in desktop simulation and virtual reality to explain Moon phases; this could indicate that the benefits of embodiment might be unique to a real, non-virtual environment.

Despite not being conducted with teacher trainees but with students aged 9 to 10 years old, in a study on matters related to the movement of molecules in different states, Hadzi-georgiou and Savage (2001) compared instruction using photographs and animations with sensorimotor activities. In our research, we obtained a medium effect size ($d = 0.46$ to $d = 0.65$) for questions related to the properties of matter (4, 5, 6) and a large effect size ($d = 1.1$ and $d = 0.9$) for questions related to phase transitions (7a and 7b), which is similar to the effect size found by these authors in their overall instruction ($d = 1.2$).

Upon reviewing these results, it becomes evident that representing simpler astronomical phenomena leads to better outcomes than attempting to model more complex and iterative ones, such as the phases of the Moon. In an inquiry-based activity, the model can be enhanced by incorporating additional elements.

To explain these improvements in learning, Richards (2012) mentions the disruption of classroom routines, the effect of bodily movement on conceptual memory, and egocentric spatial proprioception, which we also share. We also believe, as Niebert and Gropengiesser (2015) do, that the use of representations in the mesocosm can promote the understanding of phenomena.

Similarly, in a study that we would also classify as “direct embodiment”, Varelas et al. (2010) present improvements in socio-affective motivation and interest in science after working on activities related to phase changes with primary school students. In contrast,

the present study focuses on quantitative improvements in understanding matter structure, phase changes, and the role of temperature in particle movement.

The fact that there is a lack of inquiry-based studies with early schooling students (Aguilera et al., 2018), that most embodiment works have been conducted with these students (Richards, 2012), and the improved motivation observed in this student group when working with embodiment (Varelas et al., 2010) support our efforts to train future primary school teachers in these proposals.

5. Conclusions

In this work, a proposal for inquiry-based learning has been made in which modeling with embodiment has been chosen as a research strategy. We demonstrate that utilizing embodiment, the use of the body to represent or model natural systems, is an effective teaching strategy that enhances learning, particularly when studying systems in motion and vastly different from the human scale, encompassing both macroscopic and microscopic levels.

Observations indicate that students develop modeling skills, and the discussions involved in the model-building process are profound, allowing students to refine initial models and propose appropriate final models.

The questionnaire results from the experimental group surpass those of the control group, with statistically significant differences in all items related to astronomical and atomic systems. These differences yield medium and large effect sizes, with the exception of the lunar eclipse item, which shows a small effect.

The questionnaire responses indicate a greater understanding of the models compared to the control groups. Additionally, the experimental group shows a higher frequency of images with moving elements (arrows) compared to the control group.

The majority of students in the experimental group agree that embodiment is beneficial for comprehending the concepts being studied.

In summary, this study shows, in response to the research question, that inquiry-based modeling with embodiment is effective for understanding (microscopic or macroscopic) natural phenomena that typically require the use of models. The fact that students do not work directly with a given model but instead engage in an inquiry process allows them to discuss misconceptions or ideas that do not fully align with reality. These peer discussions, guided by the teacher, help students collectively progress toward the final model, which they construct by themselves. Moreover, embodiment proves effective insofar as students become more capable of adopting the model's point of view and interpreting what each of its components represents in the real world. We believe that the combination of all these elements accounts for both the effect sizes observed in the quantitative results and the progression described in the more qualitative part of this study.

This study can be extended by incorporating additional micro- and macroscopic phenomena, in order to further consolidate the proposed dynamic in the model-building process. This proposal can be easily implemented in science education, both in primary and secondary schools, and can be extended to other physical systems beyond those mentioned here, such as wave propagation, direct and alternating current, atomic and nuclear models, or nuclear and chemical reactions.

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Institutional Review Board Statement: Ethical review and approval were waived for this study, as it does not involve the collection of personal opinions or sensitive data. We consider that the study falls within the scope of ethnographic research, for which verbal consent is deemed sufficient. Nevertheless, we have ensured that the study complies with the ethical standards established by our department, and the statement has been updated accordingly.

Informed Consent Statement: Verbal informed consent was obtained from all participants. Written consent was not required because the study does not involve the collection of personal opinions or sensitive data. We consider that the study falls within the scope of ethnographic research, for which verbal consent is deemed sufficient.

Data Availability Statement: The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

IBME Inquiry-based modeling with embodiment

Appendix A

Questionnaire applied.

I have been informed of the characteristics of the Research Project. I have been able to express any questions that have arisen in this regard. I consider that I have understood this information. I am informed of the possibility of withdrawing from the study at any time. Under these conditions, I agree to participate in this study.

Name and surname:

Age:

Baccalaureate option you studied:

1.a. It depicts in a schematic drawing the phases of the Moon (as if you were an observer outside the Earth). In the drawing the Moon, the Earth and the Sun must appear. Indicate with an arrow what is the direction of movement of the Moon.

First quarter	New moon
Last quarter	Full moon

1.b. Why doesn't the lunar phase where the Earth is between the Moon and the Sun correspond each month to a lunar eclipse?

1.c. Why don't you see the new moon?

2. How can we explain, with the heliocentric model, that from the point of view of the Earth we see that a planet like Mars goes back and forth in its journey through the sky?

3. When Copernicus defended the heliocentric model, astronomers objected that how could it be, if the Earth moved, that we see the stars retain their relative position. That is, if the Earth moves, wouldn't we have to see the distance between two stars in the same constellation vary for a matter of perspective, in the same way that we see that the distance between two buildings changes as we pass by in a running car? Explains Copernicus' reasoning for answering this question.

4. How can you explain at the corpuscular (microscopic) level that the liquid changes shape, but not volume when changing the container?

5. How can you explain at the corpuscular (microscopic) level that the solid does not change shape or volume when changing the container?

6. How can you explain at the corpuscular (microscopic) level the property of gases to occupy the entire volume where they are located?
7. Imagine that a group of students have to represent the changes in state from solid to liquid and from liquid to gas, as the temperature rises. Each of them would represent a molecule of the material that, all together, they represent, while the material changes state.
- Describe what directions you would give them for representation. What would students have to do as the temperature rises? How should they be initially arranged? How does representation evolve?
 - What limitations does the representation you propose have?
- (Experimental group only)
8. Value the embodiment experience:
- Say if it has been useful to you or not, if it has helped you understand the phenomenon or any other appreciation
 - Say if you think it's applicable in a primary school classroom

Appendix B

Rating scale applied to the questionnaire questions.

Rating Scale	Item
(1) Accurately represents the Sun–Earth–Moon astronomical system, the relative positions of the three bodies in each phase, and indicates the Moon's direction of rotation.	1a
(0.5) Same as above but without indicating the direction of rotation or with an error in one of the phases.	
(0) The astronomical system is nonsensical or not represented (e.g., shows the phases as seen from Earth or something similar).	
(1) Correctly mentions the effect of alignment in the difference between lunar phase and eclipse. Not just describes what an eclipse is, but explains why the lunar phase being compared is not an eclipse.	1b
(0.5) Only describes what an eclipse is but does not explain why it does not occur every month in the corresponding lunar phase. Does not compare both phenomena. Also applies if only alignment is mentioned.	
(0) Other cases or incorrect mention of the above effect.	
(1) Complete and correct explanation using the relative positions of the Earth–Sun–Moon system.	1c
(0.5) Semi-complete explanation: Only indicates the position but does not explain.	
(0) Incorrect explanation (wrong Earth–Sun–Moon positions or refers to what would be seen “during the day,” which is not possible, etc.).	
(1) Complete and correct explanation of the retrograde motion phenomenon: refers to both the different orbital speeds and the different orbit sizes.	2
(0.5) Semi-complete explanation: Partially explains the phenomenon or explains it superficially. Mentions only speed or only orbit size.	
(0) Incorrect explanation.	
(1) Correct answer: The distance to the stars is too great in comparison to the size of Earth's orbit (Note: must say “in comparison”).	3
(0.5) Only says that we are very far away or refers to only one of the two effects.	
(0) Incorrect answer.	

Rating Scale	Item
(1) Complete explanation: Particles in a liquid feel forces that hold them together, but not as strongly as in a solid. This allows them to leave their “positions” but not stray “too far” from each other. Refers to both bonding and particle positions.	4
(0.5) Semi-complete explanation: More or less the above, but with little rigor or inappropriate language. Forgets bonding and only talks about positions or vice versa.	
(0) Incorrect explanation: Any other.	
(1) Complete explanation: The forces between particles are so strong that the lattice remains intact. This prevents them from leaving their positions or changing the distance between them. Mentions both positions and bonding.	5
(0.5) Semi-complete explanation: Same as above but less rigorous and incomplete.	
(0) Incorrect explanation: Any other. Shows the alternative idea that assigns macroscopic properties to microscopic particles.	
(1) Complete explanation: The forces between the particles are very weak, and the particles leave their positions and are not constrained by the presence of others (they can change the distance between them—almost free particles).	6
(0.5) Semi-complete explanation: Same as above but with less rigor and detail.	
(0) Incorrect explanation: Any other. Shows the alternative idea that assigns macroscopic properties to microscopic particles.	
(1) Has a clear understanding of the content and the proposed model is free of errors. Proposes the model elements and their dynamics correctly. Mentions particles, the variables of position and force between particles, and correctly describes the gradation.	7a
(0.5) Has a clear understanding of the content, but the proposed model has errors or is poorly detailed.	
(0) Does not have a clear understanding of the content, and the proposed model is very limited.	
(1) Identifies the limitations of the model (not to be confused with errors!), that is, what things it does not explain because they are not relevant.	7b
(0.5) Points out space as one of the limitations. Note if any mention of scale is made.	
(0) Does not respond appropriately.	

References

- Acher, A., Arcà, M., & Sanmartí, N. (2007). Modeling as a teaching learning process for understanding materials: A case study in primary education. *Science Education*, 91(3), 398–418. [\[CrossRef\]](#)
- Agostini, E., & Francesconi, D. (2021). Introduction to the special issue “embodied cognition and education”. *Phenomenology and the Cognitive Sciences*, 20, 417–422. [\[CrossRef\]](#)
- Aguilera, D., Martín, T., Valdivia, V., Ruiz, A., Williams, L., Vélchez, J. M., & Perales, F. J. (2018). La enseñanza de las ciencias basada en indagación. Una revisión sistemática de la producción española. *Revista de Educación*, 381, 259–284. [\[CrossRef\]](#)
- Amin, T., Jeppsson, F., & Haglund, J. (2015). Conceptual metaphor and embodied cognition in science learning: Introduction to special issue. *International Journal of Science Education*, 37(5–6), 745–758. [\[CrossRef\]](#)
- Barsalou, L. W. (2008). Grounded cognition. *Annual Review of Psychology*, 59, 617–645. [\[CrossRef\]](#)
- Brookes, D. T., Ektina, E., & Planinsic, G. (2020). Implementing an epistemologically authentic approach to student-centered inquiry learning. *Physical Review Physics Education Research*, 16(2), 020148. [\[CrossRef\]](#)
- Buty, C., Tiberghien, A., & Le Maréchal, J. F. (2004). Learning hypotheses and an associated tool to design and to analyse teaching-learning sequence. *International Journal of Science Education*, 26(5), 579–604. [\[CrossRef\]](#)
- Capps, D. K., & Crawford, B. A. (2013). Inquiry-based instruction and teaching about nature of science: Are they happening? *Journal of Science Teacher Education*, 24(3), 497–526. [\[CrossRef\]](#)

- Casado, P. (2017). From metaphor to action. Embodied language cognition. *Mètode Science Studies Journal*, 7, 45–49. [\[CrossRef\]](#)
- Clement, J. (2000). Model based learning as a key research area for science education. *International Journal of Science Education*, 22(9), 1041–1053. [\[CrossRef\]](#)
- Etkina, E., Warren, A., & Gentile, M. (2006). The role of models in physics instruction. *Physics Teacher*, 44(1), 34–39. [\[CrossRef\]](#)
- Hadzigeorgiou, Y., & Savage, M. (2001). A study of the effect of sensorimotor experiences on the retention and application of two fundamental physics ideas. *Journal of Elementary Science Education*, 13, 9–21. [\[CrossRef\]](#)
- Hernández, M. I., Couso, D., & Pintó, R. (2015). Analyzing students' learning progressions throughout a teaching sequence on acoustic properties of materials with a model-based inquiry approach. *Journal of Science Education and Technology*, 24(2), 356–377. [\[CrossRef\]](#)
- Johnson-Glenberg, M. C., Lindgren, R., Koziupa, T., Bolling, A., Nagendran, A., Birch-field, D., & Cruse, J. (2012). Serious games in embodied mixed reality learning environments. *Games, Learning and Society Conference*, 8, 353–359.
- Kolovou, M. (2022). In search of assessment shifts in embodied learning science research: A review. *Journal Science Education & Technology*, 31, 246–257. [\[CrossRef\]](#)
- Kontra, C., Lyons, D. J., Fischer, S. M., & Beilock, S. L. (2015). Physical experience enhances science learning. *Psychological Science*, 26(6), 737–749. [\[CrossRef\]](#)
- Lakoff, G., & Johnson, M. (2008). *Metaphors we live by*. University of Chicago Press.
- Lindgren, R., & Moshell, J. M. (2011, June 20–23). *Supporting children's learning with body-based metaphors in a mixed reality environment*. The 10th International Conference on Interaction Design and Children (pp. 177–180), Ann Arbor, MI, USA. [\[CrossRef\]](#)
- Madden, J., Pandita, S., Schuldt, J., Kim, B., Won, A., & Holmes, N. (2020). Ready student one: Exploring the predictors of student learning in virtual reality. *PLoS ONE*, 15(3), e0229788. [\[CrossRef\]](#)
- Minner, D. D., Levy, A. J., & Century, J. (2010). Inquiry-based science instruction-what is it and does it matter? Results from a research synthesis years 1984 to 2002. *Journal of Research in Science Teaching*, 47(4), 474–496. [\[CrossRef\]](#)
- National Research Council. (1996). *National science education standards*. National Academy.
- Niebert, K., & Gropengiesser, H. (2015). Understanding starts in the mesocosm: Conceptual metaphor as a framework for external representations in science teaching. *International Journal of Science Education*, 37(5–6), 903–933. [\[CrossRef\]](#)
- Oliva, J. M. (2019). Distintas acepciones para la idea de modelización en la enseñanza de las ciencias. *Enseñanza de las Ciencias*, 37(2), 5–24. [\[CrossRef\]](#)
- Palomar, R., & Solbes, J. (2015). Evaluación de una propuesta para la enseñanza y el aprendizaje de la astronomía en secundaria. *Enseñanza de las Ciencias*, 33(2), 91–111. [\[CrossRef\]](#)
- Pedaste, M., Mäeots, M., Siiman, L. A., de Jong, T., van Riesen, S. A. N., Kamp, E. T., Manoli, C. C., Zacharia, Z. C., & Tsourlidaki, E. (2015). Phases of inquiry-based learning: Definitions and the inquiry cycle. *Educational Research Review*, 14, 47–61. [\[CrossRef\]](#)
- Peffer, M. E., Beckler, M. L., Schunn, C., Renken, M., & Revak, A. (2015). Science Classroom Inquiry (SCI) simulations: A novel method to scaffold science learning. *PLoS ONE*, 10(3), e0120638. [\[CrossRef\]](#) [\[PubMed\]](#)
- Plummer, J. D. (2009). Early elementary students' development of astronomy concepts in the planetarium. *Journal of Research in Science Teaching: The Official Journal of the National Association for Research in Science Teaching*, 46(2), 192–209. [\[CrossRef\]](#)
- Plummer, J. D. (2014). Spatial thinking as the dimension of progress in an astronomy learning progression. *Studies in Science Education*, 50(1), 1–45. [\[CrossRef\]](#)
- Porro, C. A., Francescato, M. P., Cettolo, V., Diamond, M. E., Baraldi, P., Zuiani, C., Bazzocchi, M., & di Prampero, P. E. (1996). Primary motor and sensory cortex activation during motor performance and motor imagery: A Functional magnetic resonance imaging study. *Journal of Neuroscience*, 16(23), 7688–7698. [\[CrossRef\]](#)
- Pozo, J. I. (2017). Learning beyond the body: From embodied representations to explication mediated by external representations. *Infancia y Aprendizaje*, 40(2), 219–276. [\[CrossRef\]](#)
- Richards, T. (2012). Using kinesthetic activities to teach Ptolemaic and Copernican retrograde motion. *Science & Education*, 21, 899–910. [\[CrossRef\]](#)
- Schwarz, C. V., Reiser, B. J., Davis, E. A., Kenyon, L., Achér, A., Fortus, D., Shwartz, Y., Hug, B., & Krajcik, J. (2009). Developing a learning progression for scientific modeling: Making scientific modeling accessible and meaningful for learners. *Journal of Research in Science Teaching*, 46(6), 632–654. [\[CrossRef\]](#)
- Trundle, K., Atwood, R., & Christopher, J. (2002). Preservice elementary teachers' conceptions of moon phases before and after instruction. *Journal of Research in Science Teaching: The Official Journal of the National Association for Research in Science Teaching*, 39(7), 633–658. [\[CrossRef\]](#)
- Tuzón, P., & Solbes, J. (2016). Particle physics in high school: A diagnose study. *PLoS ONE*, 11(6), e0156526. [\[CrossRef\]](#)
- Tuzón, P., & Solbes, J. (2017). La modelización usando corporeización en la enseñanza de las ciencias. *Enseñanza de las Ciencias, n° extra*, 587–594.
- Tuzón, P., & Solbes, J. (2024). The use of embodiment to teach updated models of matter components and interactions in secondary school. *Physics Education*, 59(4), 045027. [\[CrossRef\]](#)

- Van Der Valk, T., Van Driel, J. H., & De Vos, W. (2007). Common characteristics of models in present-day scientific practice. *Research in Science Education*, 37, 469–488. [\[CrossRef\]](#)
- Van Driel, J. H., & Verloop, V. (2002). Experienced teachers' knowledge of teaching and learning of models and modelling in science education. *International Journal of Science Education*, 24, 1255–1272. [\[CrossRef\]](#)
- Varelas, V., Pappas, C. C., Tucker-Raymond, E., Kane, J., Hanks, J., Ortiz, I., & Keblawe-Shamah, N. (2010). Drama activities as ideational resources for primary-grade children in urban science classrooms. *Journal of Research in Science Teaching*, 47(3), 302–325. [\[CrossRef\]](#)
- Vo, D. V., & Simmie, G. M. (2024). Assessing scientific inquiry: A systematic literature review of tasks, tools and techniques. *International Journal of Science and Mathematics Education*, 23(4), 871–906. [\[CrossRef\]](#)
- Wallon, R. C., & Lindgren, R. (2017). Considerations for the design of gesture-augmented learning environments. In M. J. Spector, B. B. Lockee, & M. D. Childress (Eds.), *Learning, design, and technology: An International compendium of theory, research, practice, and policy* (pp. 1–21). Springer. [\[CrossRef\]](#)
- Windmiller, G., Blanco, P., & Welsh, W. (2021). Developing virtual reality activities for the astro 101 class and lab. In G. Schultz, J. Barnes, F. Andrew, & L. Shore (Eds.), *ASP2020: Embracing the future: Astronomy Teaching and public engagement asp conference series* (Vol. 531, p. 285). Astronomical Society of the Pacific.
- Windschitl, M., Thompson, J., & Braaten, M. (2008). Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigations. *Science Education*, 92(5), 941–967. [\[CrossRef\]](#)

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