Integrating laboratory activities and visual representations to foster students' understanding of basic astronomy phenomena: an example about seasonal changes – Electronic Supplemental Material

S1. Teaching module "Causes of seasons"

Description of the teaching-learning activities

In the first activity (1 hour), the students in small groups are guided by the teacher through a written worksheet to reflect on the possible factors underlying the cause of seasons and are asked to design an experiment to show the relevance of the factors identified. In the second activity (2 hours), the students in small groups first measure with a voltmeter the output voltage of a photovoltaic panel lit by an incandescent lamp when the distance between the source and the panel changes and the panel is held fixed so that the radiation in the latter situation impinges at 90° degrees onto the panel. Then, the students repeat the experiment by changing the inclination of the panel with respect to the direction of the incoming radiation in the interval [0 – 85] degrees at a fixed distance from the light source. The students are guided to infer from their own measurements the mathematical relationships between the radiation flow across a surface, i.e., the output power of the panel and: (i) the distance between the panel surface and the light source (inverse square distance law); (ii) the angle between the normal to the panel surface and the direction of the incident radiation (cosine law). Finally, in the third activity (1 hour), the students are first asked to use the cosine law to evaluate the incident radiation flow at specific times of the year in five climatic zones: winter and summer solstices at the tropics and Equator, summer/winter solstices and autumn/spring equinoxes at the Arctic and Antarctic circle, respectively. Then, the students are asked to apply the inverse square law of the incident radiation when the Earth is at the aphelion and at the perihelion – using the corresponding values of the Earth-Sun distance – independently on the location of the observer on Earth' surface. Hence, by comparing the results of the two laws for the incident radiation – the cosine and inverse square law – the students are guided to understand that the effect of the tilt of the Earth's axis is predominant with respect to the small eccentricity (3%) of the Earth's orbit in the explanation of the change of seasons. During this phase, the students are asked to compare the values of the Earth-Sun distance at the aphelion and at the perihelion, so to infer that the Earth's orbit is almost circular and that the variable angle of incidence must provide the correct explanation of seasons. This reasoning is also supported by explicitly calculating which would be the difference between the Earth-Sun distance at aphelion and at the perihelion to obtain the same variation obtained by changing the inclination of the incident radiation. More details, including example measurements, are reported in the Supplemental Material.

Student worksheets

First activity: *"Why do we experience different seasons?"* (1h)

1. What do you think are the factors that influence the changing of the seasons?
2. Explain how each of the factors identified influences the changing of the seasons.
3. Indicate for each of the factors identified what effect its absence would have on the alternation of seasons.
4. Indicate any relationship between the factors identified in the previous activity.
5. Design an experiment that shows the influence on the changing of the seasons of one or more of the factors you identified. Specify the objective of the experiment, any measuring instruments and materials needed and the procedure you would follow.

Second activity: *"How do the Earth's axis inclination and the distance between the Earth and Sun affect seasons' change"* (2h)

Notes for teachers: in this activity, the students will use a photovoltaic panel. To make the experimental setting as much as possible closer to the real Earth-Sun system, the distance between the panel and the light source should be between 3 m and 5 m.. It is important to discuss with the students when it is important to model sunrays as parallel or not. A black cardboard cylinder can be used to make the light rays almost parallel when changing the panel's inclination. The solar panel can be presented as a black box, emphasizing its role as a tool to indirectly measure the energy flow. To this aim, it is possible to recall that a solar panel is used as an energy transformation system in real-world applications as house water heating.

1. Predict qualitatively (in words and with a graph) what happens when the angle of incidence of the light beam on the surface of the panel varies
2. Predict qualitatively what happens when the distance of the source from the surface of the panel varies.
3. Now measure the panel output voltage for different angles (between 15° and 75°) and construct a table of the measured data.
4. Observe the data in the table, graph them on graph paper and compare the trend with your predictions. Qualitatively explain the voltage trend as the angle of incidence of the light beam on the panel surface changes.

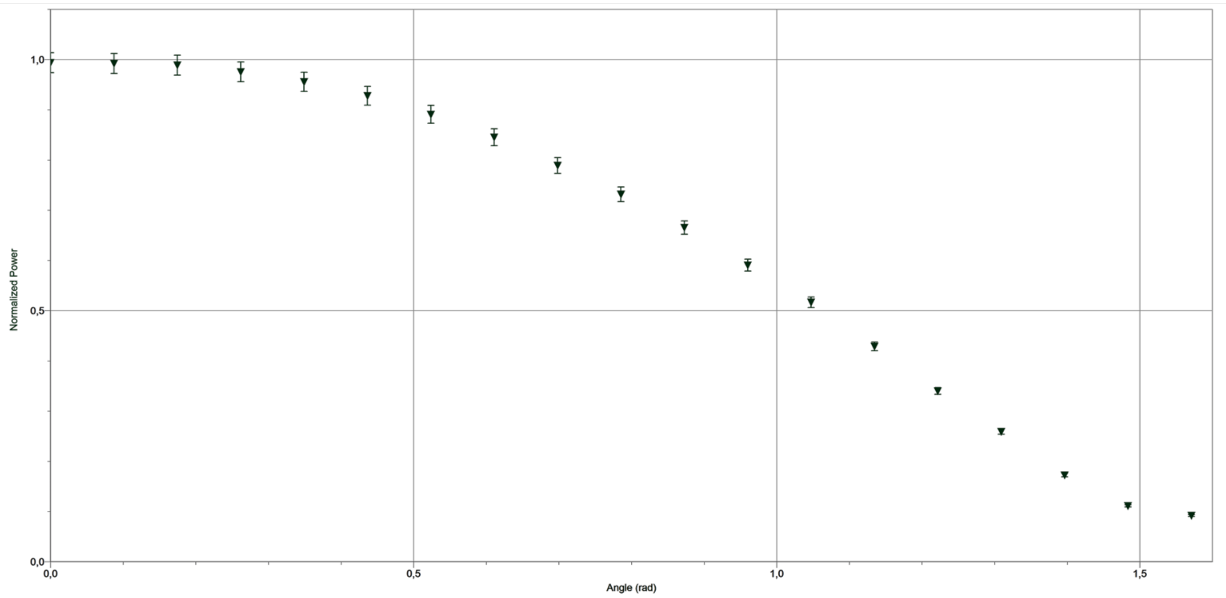


Figure S1. Example measurement of the panel output voltage as a function of the angle between the normal to the surface and the direction of the incident radiation. Fitting curve equation: $P(\theta) = A\cos(\theta) + B; A = 0.98 \pm 0.01; B = 0.03 \pm 0.01$

5. Now measure the output voltage from the panel for different distances (d) and construct a table of the measured data.
6. Observe the data in the table in a graph and compare the trend with your predictions. Qualitatively explain the voltage trend as the distance of the beam source from the panel surface changes

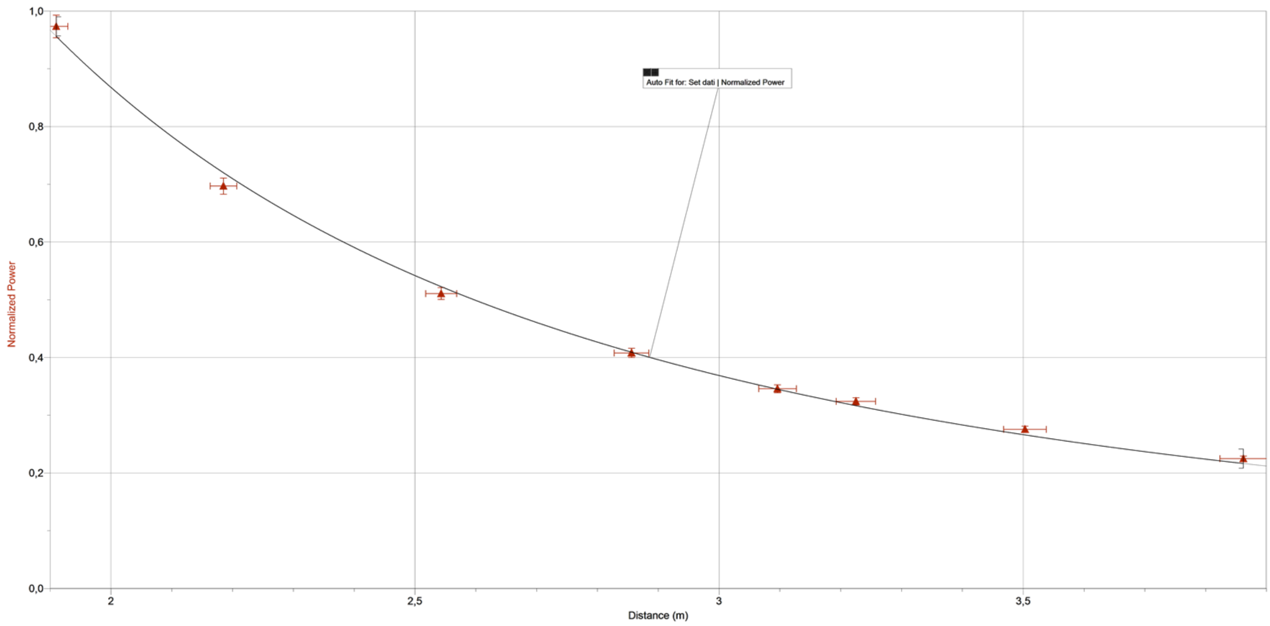


Figure S2. Example measurement of the panel output normalized power as a function of the distance between the panel surface and the light source. Fitting curve equation: $P(d) = \frac{A}{d^{2+B}}$; $A = (3.7 \pm 0.1)m^2; B = 0.11 \pm 0.05$

Third activity: ***"What influences most between distance and axis inclination?"*** (1h)

1. Observe the following figure. Determine, from the previous laws obtained in your experiments, the power/energy measured by the panel for angles corresponding to different latitudes on the days of the spring/autumn equinox and the summer/winter solstice (to help you, you can write down the values on the figure at the marked angles). What evidence do the calculated values suggest to you?

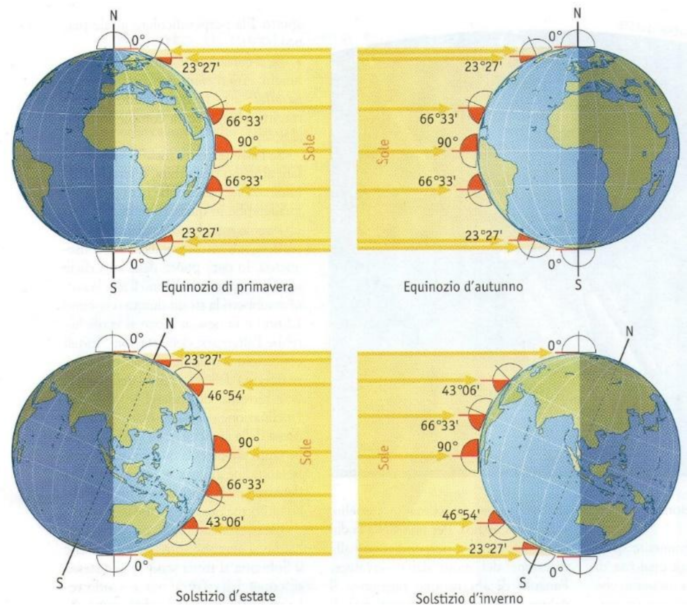


Figure S3. Sunrays incident angles at different locations on the Earth at spring equinox (top left), autumn equinox (top right), summer solstice (bottom left) and winter solstice (bottom right). Used by permission from Zanichelli.

2. Observe the following figure. Starting from a distance of *3m,* how close should you bring the light source to the panel to simulate the difference between aphelion (152x106 km) and perihelion (147x106 km) of the Earth's orbit? Justify your answer.

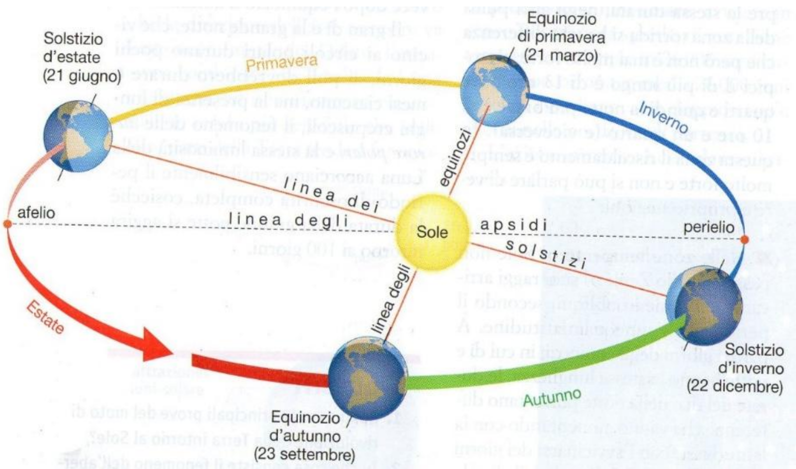


Figure S4. Earth's orbit during a year. Used by permission from Zanichelli.

3. What would be the difference between the Earth-Sun distance at aphelion and at the perihelion to obtain the same variation obtained by changing the inclination of the incident radiation?
4. Determine, from the previous laws obtained in your experiments, the power/energy measured by the panel at the two identified positions: aphelion and perihelion. Comment briefly on the result obtained.

S2. Image-based teaching activities

In all conditions, the activity sequence lasted 2 hours. The students are given a teaching booklet (see below). After reading the booklet, the teacher summarizes the information and guides the students to relate the features of the studied images, when present, to the mechanism underlying seasonal changes relating the different inclination of sunrays on observer's plane to the Earth's axis tilt and the motion on the quasi-circular orbit.

Booklet introduction

The texts you are about to read are about seasonal changes, which involve our planet and the Sun. The distances involved in this phenomenon, e.g., radius of the Earth, radius of the Sun, Earth-Sun distance are enormous and differ from each other by many orders of magnitude. For example, the Earth-Moon distance is much smaller than the Earth-Sun distance. For this reason, it is impossible to reproduce in an image, the dimensions of celestial bodies and their distances using the same scale. We therefore invite you to be careful when looking at any images in the following texts.

Booklet for the "Textbook images" condition

The alternation of the seasons is a consequence of the combination of two factors: the Earth's motion of revolution around the Sun and the constant inclination of the Earth's axis with respect to the plane of the Earth's orbit (Fig. S5).

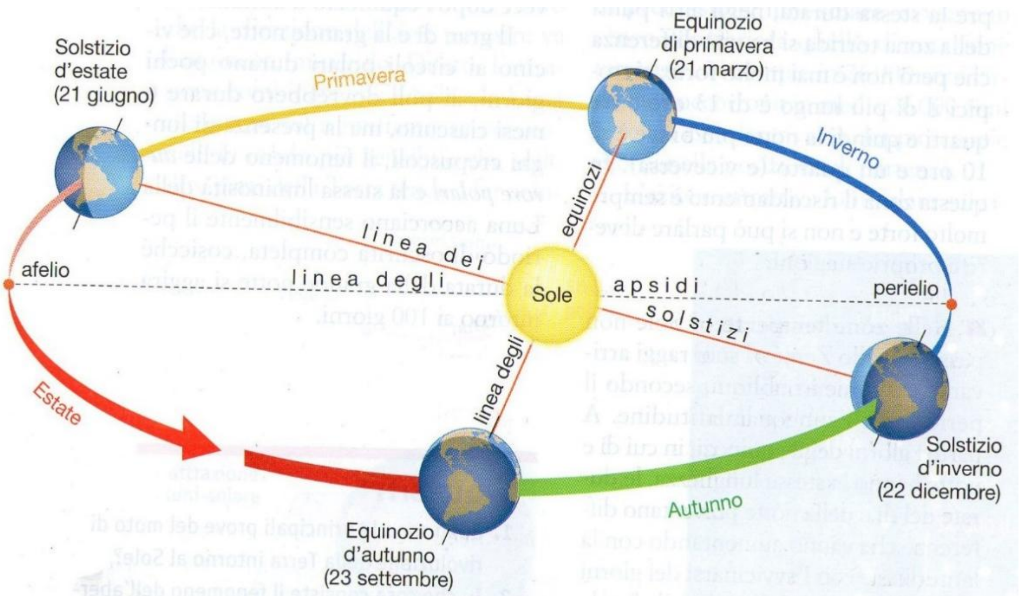


Figure S5. The Earth moves along an orbit that has the shape of an ellipse, of which the Sun occupies one of the foci. Due to this shape of the orbit, the distance between the Earth and the Sun varies throughout the year. The perihelion is the closest point in the orbit to the Sun; the aphelion is the farthest point from the Sun. The average Earth-Sun distance is about 149600000 km. Used by permission from Zanichelli.

Over the course of a year, the Earth moves along an orbit that has the shape of a slightly eccentric ellipse, of which the Sun occupies one of the foci. Because of this shape of the orbit, the distance between the Earth and the Sun varies throughout the year, albeit slightly. Perihelion is the closest point in the orbit to the Sun; aphelion is the farthest point from the Sun. The average Earth-Sun distance is about 149600000 km.

The motion of the Earth around the Sun is not the only movement that the Earth makes, it also rotates on itself in 24 hours. The Earth's axis of rotation is not perpendicular to the plane in which the Earth's orbit lies and forms an angle of 23°27' with an imaginary straight line perpendicular to that plane.

During the Earth's rotation, its axis of rotation never changes direction and remains parallel to itself.

One consequence of the tilt of the Earth's axis of rotation relative to the plane of the Earth's orbit is that the way the Sun's rays hit the Earth's surface at a given location changes throughout the year. In particular, it changes the angle they form with the surface at a given point on the Earth's surface. The greater the angle that the sun's rays form with the earth's surface, the greater the energy they transmit to a given portion of the earth's surface. Consequently, in a certain area of the Earth, summer corresponds to the period of the year when the Sun's rays hit the Earth's surface with a greater inclination than in the rest of the year, vice versa there is winter when the inclination with which the sun's rays hit the Earth is lower than the rest of the year. We can therefore say that the alternation of the seasons is a consequence of the combination of two factors: the motion of revolution of the Earth around the Sun and the constant inclination of the Earth's axis with respect to the plane of the Earth's orbit.

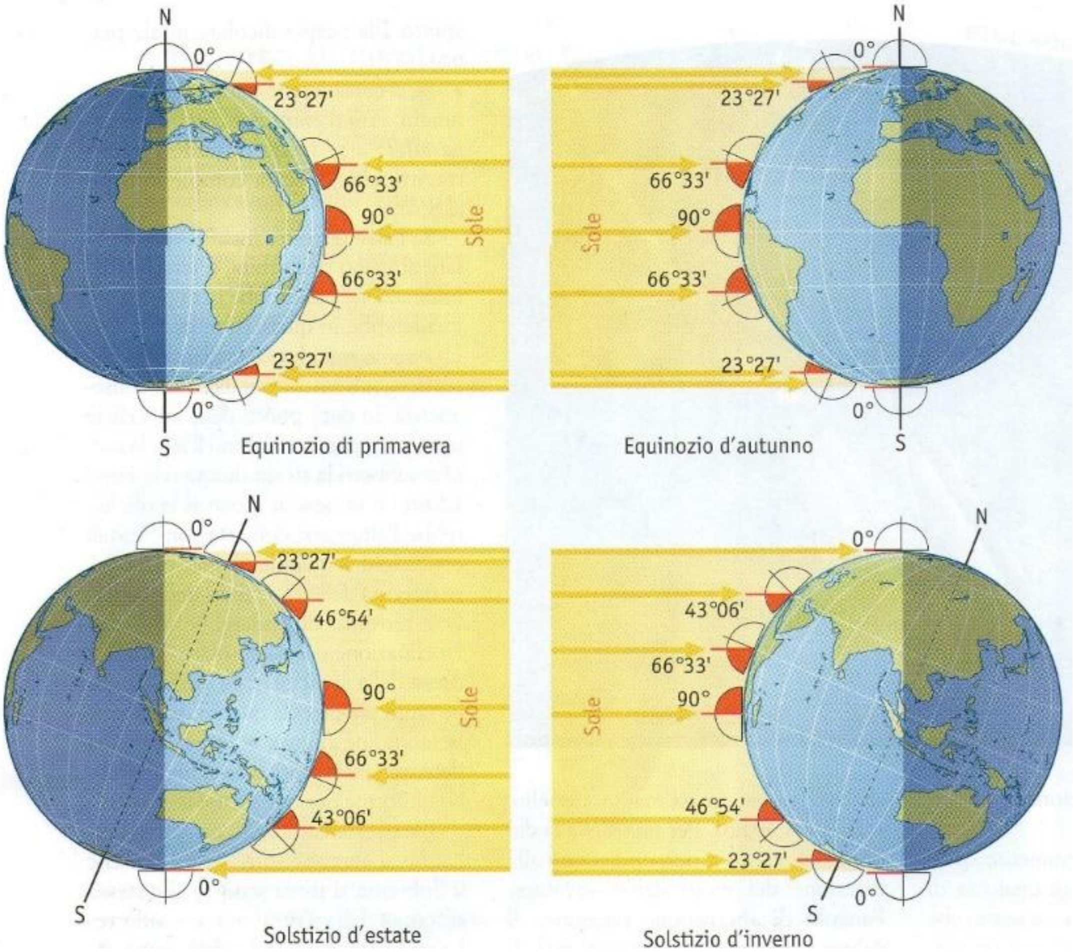


Figure S6. Sunrays incident angles at different locations on the Earth at spring equinox (top left), autumn equinox (top right), summer solstice (bottom left) and winter solstice (bottom right). Used by permission from Zanichelli.

Booklet for the "Specially designed images" condition

Seasonal change is a consequence of the combination of two factors: the Earth's motion of revolution around the Sun and the constant inclination of the Earth's axis with respect to the plane of the Earth's orbit. The axis of rotation of the Earth, as shown in figure 1, is not perpendicular to the plane in which the Earth's orbit lies, and forms an angle of 23°27' with an imaginary line perpendicular to this plane. During the Earth's rotation, its axis of rotation never changes direction and remains parallel to itself. The Earth moves along an orbit that has the shape of a slightly eccentric ellipse, of which the Sun occupies one of the foci (see next figure). Because of this shape of the orbit, the distance between the Earth and the Sun varies throughout the year, albeit slightly. Perihelion is the closest point in the orbit to the Sun; aphelion is the farthest point from the Sun. The average Earth-Sun distance is about 149600000 km.

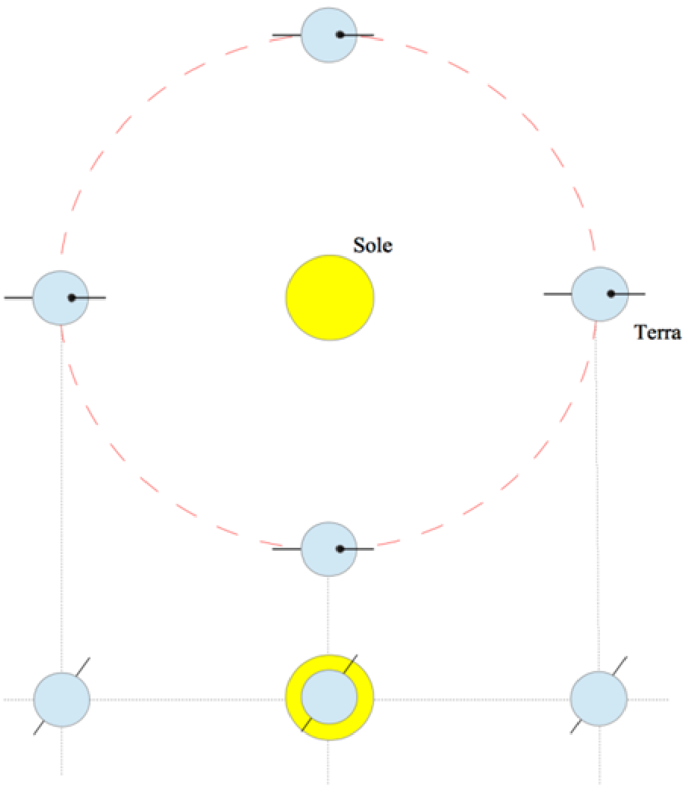


Figure S7: *In the upper part of the figure you can see the orbit described by the Earth around the Sun seen from above (dotted curve in red), from this perspective it appears as an almost perfect circle. In the image you can see how the Earth would look in various positions along the orbit, the Earth's axis of rotation is also represented, which is not perpendicular to the plane of the Earth's orbit and during the motion of revolution of our planet it always remains parallel to itself.*
At the bottom of the image you can see the Earth in different positions as an observer would see it on the plane that contains the Earth's orbit.

One consequence of the tilt of the Earth's axis of rotation is that the way the Sun's rays hit the Earth's surface at a given location changes throughout the year. In particular, it changes the angle they form with the surface of the Earth. The next figure shows how, depending on the different position of the Earth along its orbit, the sun's rays come to hit the Earth's surface at different angles. The greater the angle that the sun's rays form with the earth's surface, the greater the energy they transmit to a given portion of the earth's surface. Consequently, in a certain area of the Earth, summer corresponds to the period of the year when the Sun's rays hit the Earth's surface with a greater inclination than in the rest of the year, vice versa there is winter when the inclination with which the sun's rays hit the Earth is lower than the rest of the year.

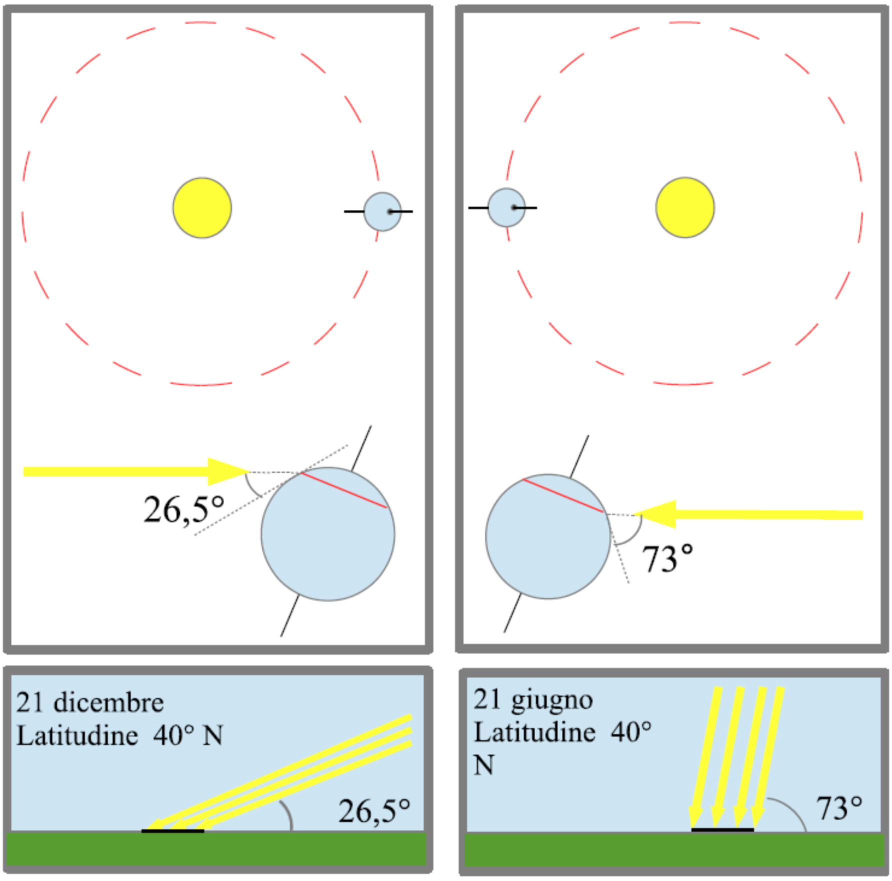


Figure S8. *In the panel on the left, we depict the situation that occurs on December 21 in a location at 40° latitude. On that date, in this locality, the sun's rays form an angle of 26.5° with respect to the plane of the horizon. In the right panel, the situation that occurs in the same location on June 21st is represented. On this date, in this location, the sun's rays form an angle of 73° with respect to the plane of the horizon.*

Booklet for the "No images" condition

The alternation of the seasons is a consequence of the combination of two factors: the Earth's motion of revolution around the Sun and the constant inclination of the Earth's axis with respect to the plane of the Earth's orbit.

Over the course of a year, the Earth moves along an orbit that has the shape of a slightly eccentric ellipse, of which the Sun occupies one of the foci. Because of this shape of the orbit, the distance between the Earth and the Sun varies throughout the year, albeit slightly. Perihelion is the closest point in the orbit to the Sun; aphelion is the farthest point from the Sun. The average Earth-Sun distance is about 149600000 km.

The motion of the Earth around the Sun is not the only movement that the Earth makes, it also rotates on itself in 24 hours. The Earth's axis of rotation is not perpendicular to the plane in which the Earth's orbit lies, and forms an angle of 23°27' with an imaginary straight line perpendicular to that plane.

During the Earth's rotation, its axis of rotation never changes direction and remains parallel to itself.

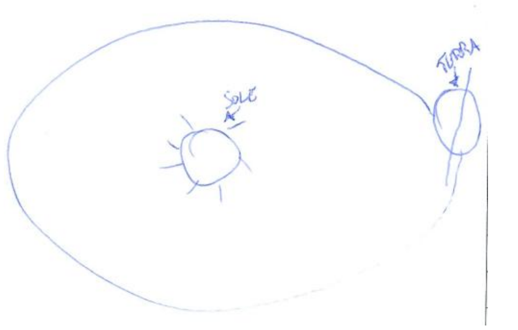
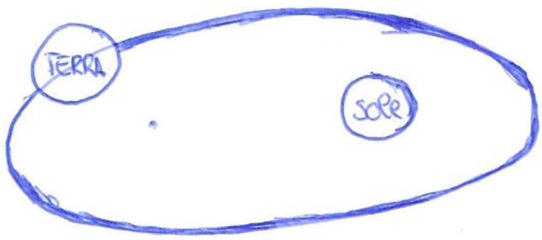
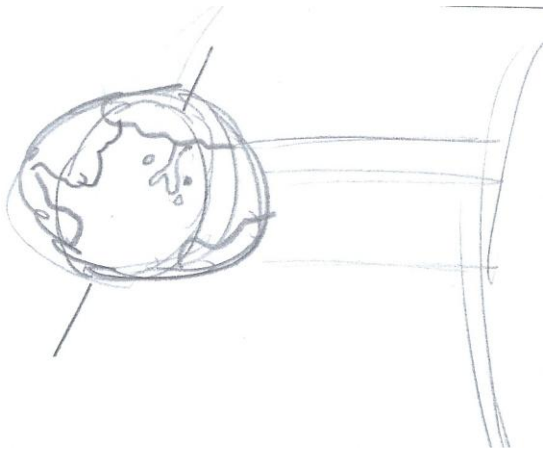
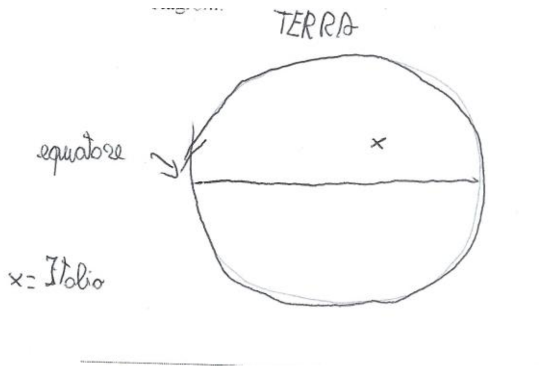
One consequence of the tilt of the Earth's axis of rotation relative to the plane of the Earth's orbit is that the way the Sun's rays hit the Earth's surface at a given location changes throughout the year. In particular, it changes the angle they form with the surface at a given point on the Earth's surface. The greater the angle that the sun's rays form with the earth's surface, the greater the energy they transmit to a given portion of the earth's surface. Consequently, in a certain area of the Earth, summer corresponds to the period of the year when the Sun's rays hit the Earth's surface with a greater inclination than in the rest of the year, vice versa there is winter when the inclination with which the sun's rays hit the Earth is lower than the rest of the year. We can therefore say that the alternation of the seasons is a consequence of the combination of two factors: the motion of revolution of the Earth around the Sun and the constant inclination of the Earth's axis with respect to the plane of the Earth's orbit.

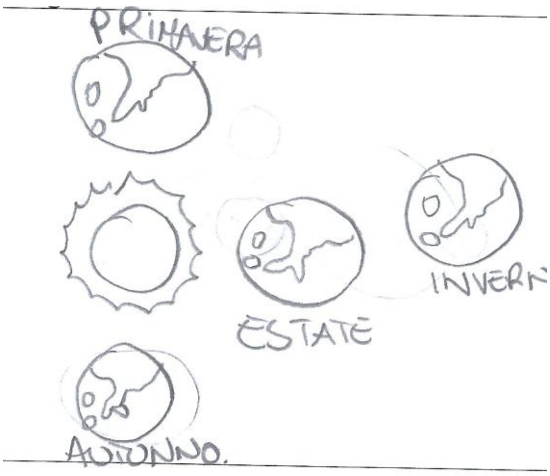
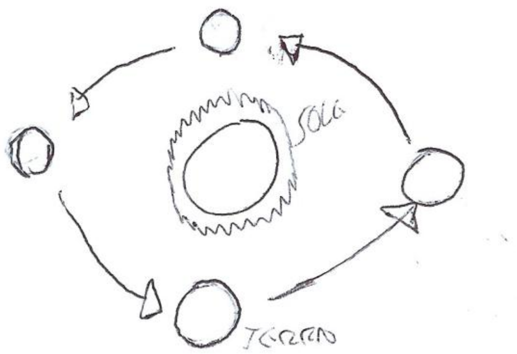
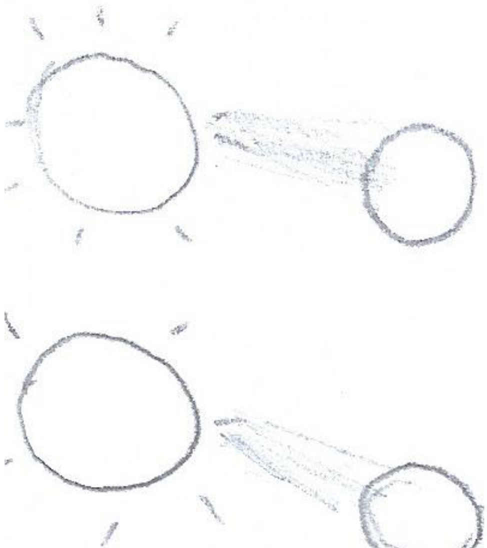
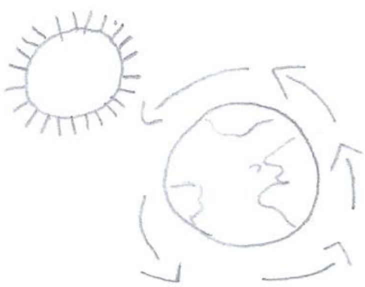
S3. Example of coding of drawings

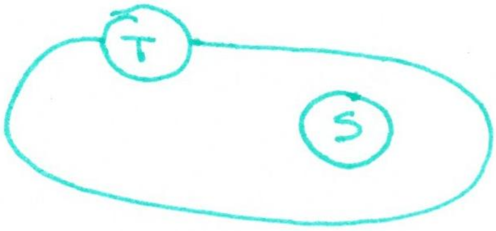
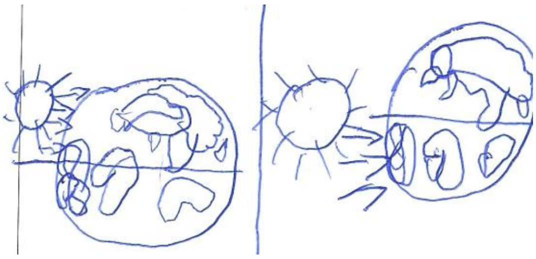
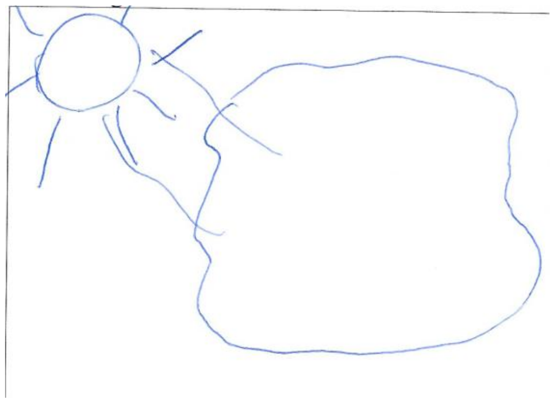
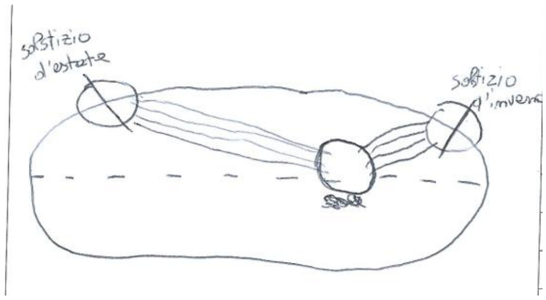
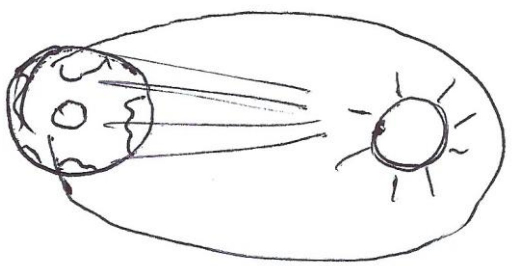
In Table S1, we report the list of the graphical elements that we used to code the students' drawings. An example of student-produced visual representation is also reported

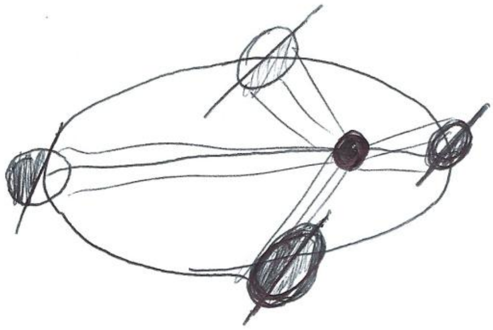
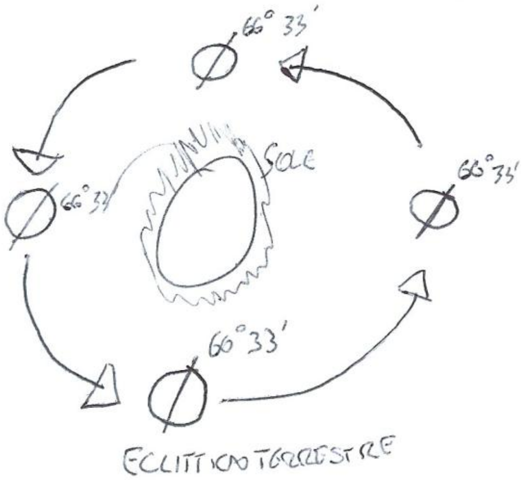
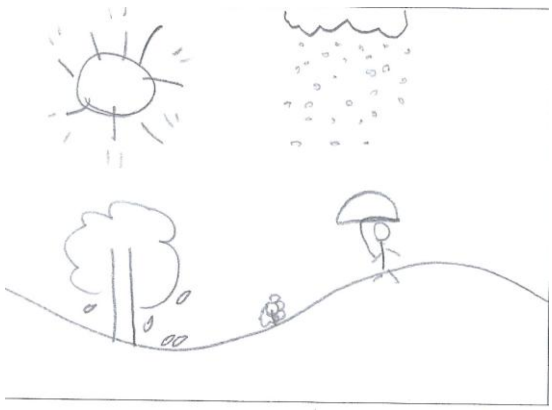
Table S1

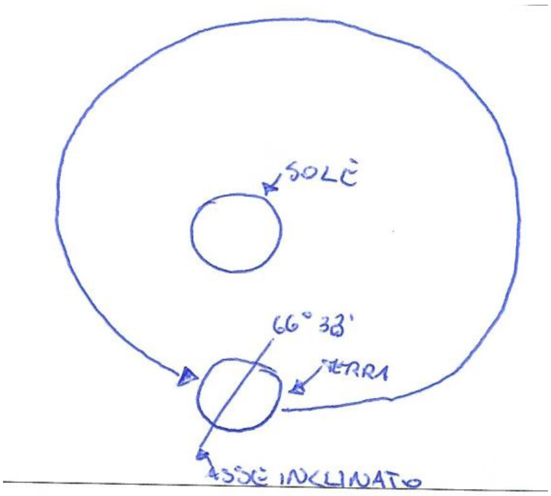
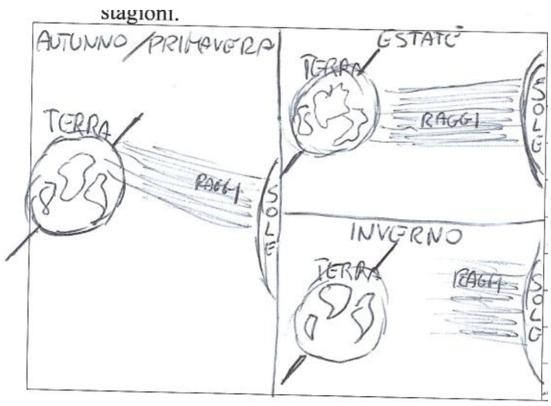
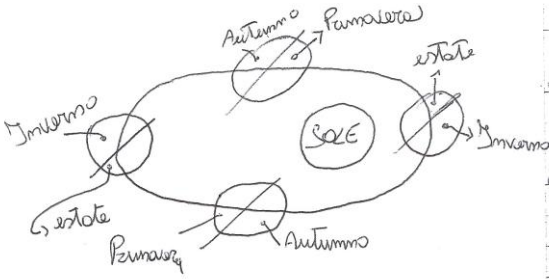
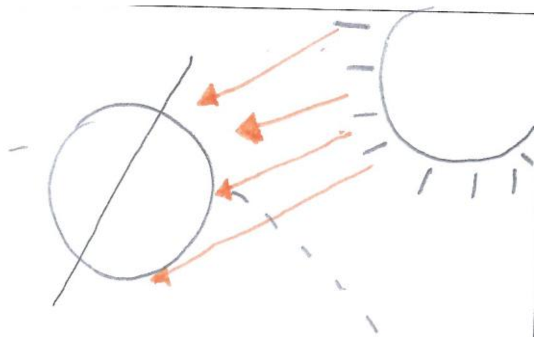
Description of the graphical elements used to code the students' drawings.

Code	Element	Pictorial description	Example
S1	Orbit	Closed empty circle with continuous or dotted border which encompasses other elements inside or has elements on its border (Translation of words: Sun, Earth)	
S2	Elliptical orbit	Element described in S1 with an elliptical form (Translation of words: Aphelion, Foci, Sun, Perihelion, Earth)	
S3	Earth	A dot or a closed empty/filled circle with irregular lines on its face	
S4	One Earth	Only one element described in S3 (Translation of words: Earth, Sun)	
S5	Multiple Earth	At least two elements described in S3	

			
S6	Multiple Earth and orbit	At least two elements described in S3 with the elements described in S1 (Translation of words: Earth, Sun)	
S7	Multiple Earth and no orbit	At least two elements described in S3 without the elements described in S1	
S8	Sun	A dot or a closed empty/filled circle with segments near the border and with no elements inside	

S9	Sun and orbit	One or more elements described in S8 + S1 (Translation of words: Earth, Sun)	
S10	Sun and no orbit	One or more elements described in S8 without the element described in S1 (Translation of words: Earth, Sun, Goes Away)	
S11	Rays	Segments between two or more circular elements	
S12	Hitting rays	Elements described in S11 near the element described in S3 (Translation of words: Earth, Sun, Goes Away)	
S13	Converging rays	Convergent segments between two or more elements and near the element described in S3	

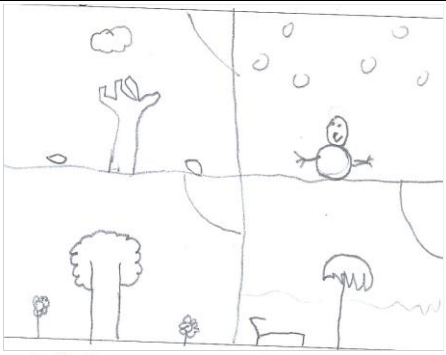
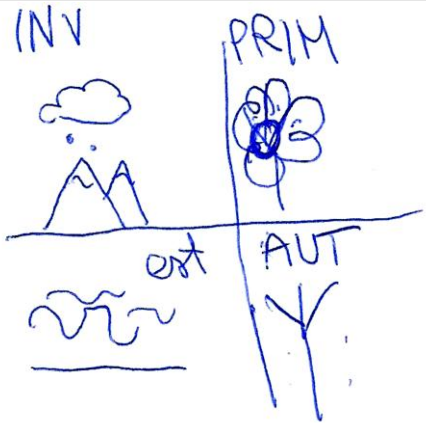
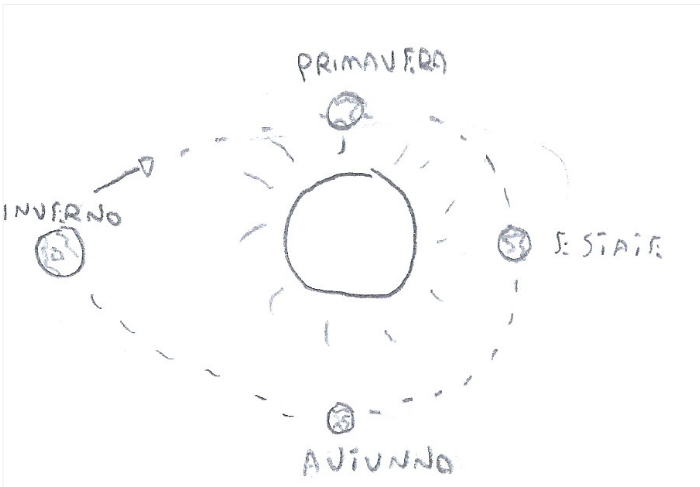
S14	Inclined rays	Elements described in S13 with different inclinations (Translation of words: Sunrays, Earth, Winter, Summer, Earth, Sunrays)	
S15	Distance	Only one segment that connects the elements described in S3 and S8 (Translation of words: Earth, Aphelion, Sun, Perihelion)	
S16	Earth’s axis	Inclined or vertical segment that intersects the element described in S3 (Translation of words: Sun)	
S17	Weather	Elements related to climate or weather as sea, beach, snowman	

S18	Angle	Arc between two lines or segments with a numerical indication	
S19	Two drawings	Two or more frames each one with one or more graphical elements inside	
S20	Verbal	Words, numbers, or letters (Translation of words: Autumn, Sun, Winter, Summer, Spring)	
S21	Symbols	Arrows, math symbols	

In Table S2, we report the list of the graphical elements of Table S1 that univocally characterizes each category, and some example drawings. See Author (2023) the complete description of the categories.

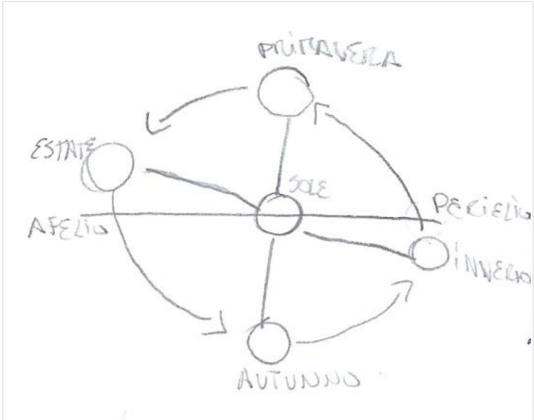
Table S2

Description of the categories used to group the students' drawings

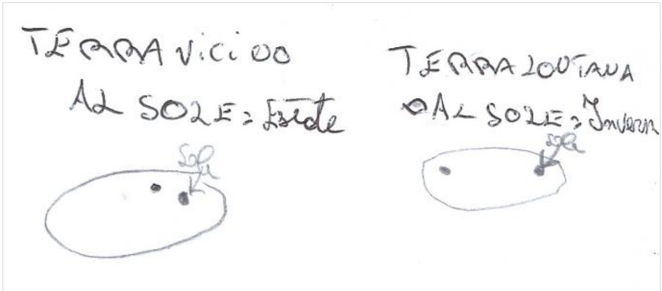
Category	Element	Example Drawing
Naïve		
	Weather	
	Two drawings	
Distance-based		
	Earth	
	Multiple Earth	
	Multiple Earth and no orbit	
	One Earth	
	Rays	

Sun

Sun and no orbit



Two drawings



Inclination-based

Angle

Converging rays

Distance

Earth

Earth's axis

Elliptical orbit

Hitting rays

Inclined rays

Multiple Earth

Multiple Earth and orbit

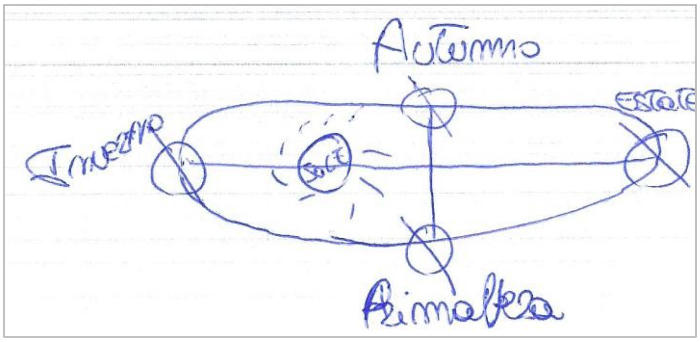
Orbit

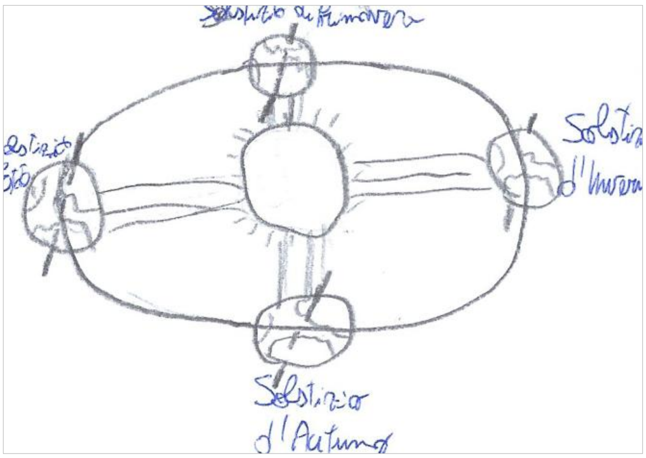
Rays

Sun

Sun and no orbit

Sun and orbit

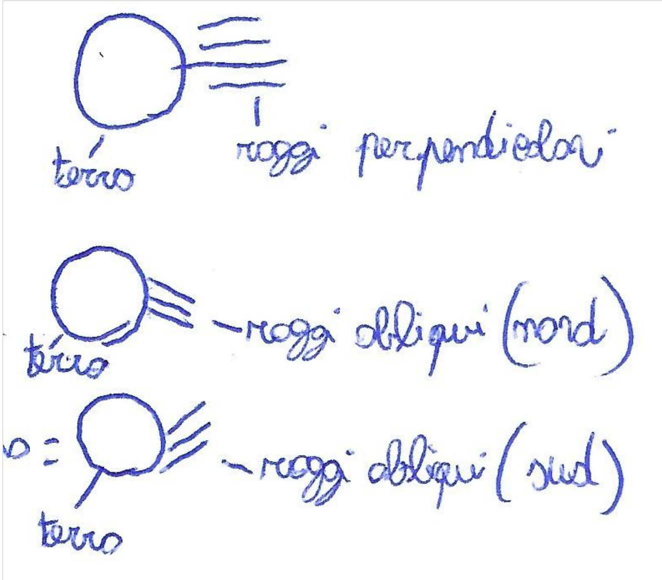




Symbols

Two drawings

Verbal



S4. Example of coding of explanations

The initial categories adopted to code the students' explanations are reported in Table S3. The macro-categories obtained after collapsing the Unclear, Distance-based and Mixed incorrect answers are also reported.

Table S3.

Categorization scheme used to code students' explanations

Macro-categories	Category	Description	Examples from the dataset
Incorrect	Unclear	The student presents tautological, wrong, unclear or too short sentences that do not allow researcher to understand the idea that student wants to communicate.	• *Seasons are identified by the area of intersection between the line of equinoxes and of solstices*
	Distance-based	The student presents a set of statements in which the main ideas is that the most important factor underlying seasonal changes is the changing distance between the Earth and the Sun.	• *It [change of seasons] happens because the distance between the Earth and the Sun changes* • *When a planet is in aphelion (closer to the Sun) it is hotter, when it is in perihelion (further to the Sun) it is colder*
	Mixed incorrect	The student may refer to some mechanisms that are conceptually wrong or not relevant to seasonal changes or the association of the factors does not present a logical sequence of relations.	• *Because the earth rotates around itself* • *In Italy, this phenomenon happens because the Earth does a movement of rotation around the Sun and thus it changes the position of the Earth with respect to the Sun and the inclination of rays. Furthermore the Earth rotates upon itself and thus in the two hemispheres seasons alternate* • *The phenomenon of seasonal changes is caused by the movements of the Earth's axis [that bring the Earth] closer to the Sun*
Partial	-	The student describes the seasonal changes in terms of simple observable consequences of seasonal changes.	• *[The change of seasons] happens because of solar rays inclination* • *Change of seasons happen because of the revolution motion that the Earth does around the Sun*
Correct	-	The student reports one or more correct factors (e.g., orbital motion, tilt of Earth's) underlying seasonal changes with a simple conceptual sequencing. The student reports all the relevant factors and provides a casual mechanism based also on physical laws	• *[seasonal changes happen] because, as the Earth moves around the Sun, it is hit by solar rays in different ways, this cause changes in heat and temperature in that part of the globe.* • *During its revolutionary period the Earth is hit in different way by sunrays* • *As the Earth has an inclined axe, when it revolves around the Sun, the points where the Earth is hit in better way by solar rays change. In Italy in winter sunrays do not arrive perpendicular, as in summer*

S5 Relationships between the multiple correspondence analysis factorial scores and categories of drawings and explanations.

In Figures S9 and S10 we report the mean MCA factorial score for each of the categories of drawings (Figure S9) and explanations (Figure S10). The differences across the categories are, as expected, significant: Welch's $F_{2,203.439} = 454.202$, $p < .001$, Welch's $F_{2,105.898} = 1047.503$, $p < .001$; respectively.

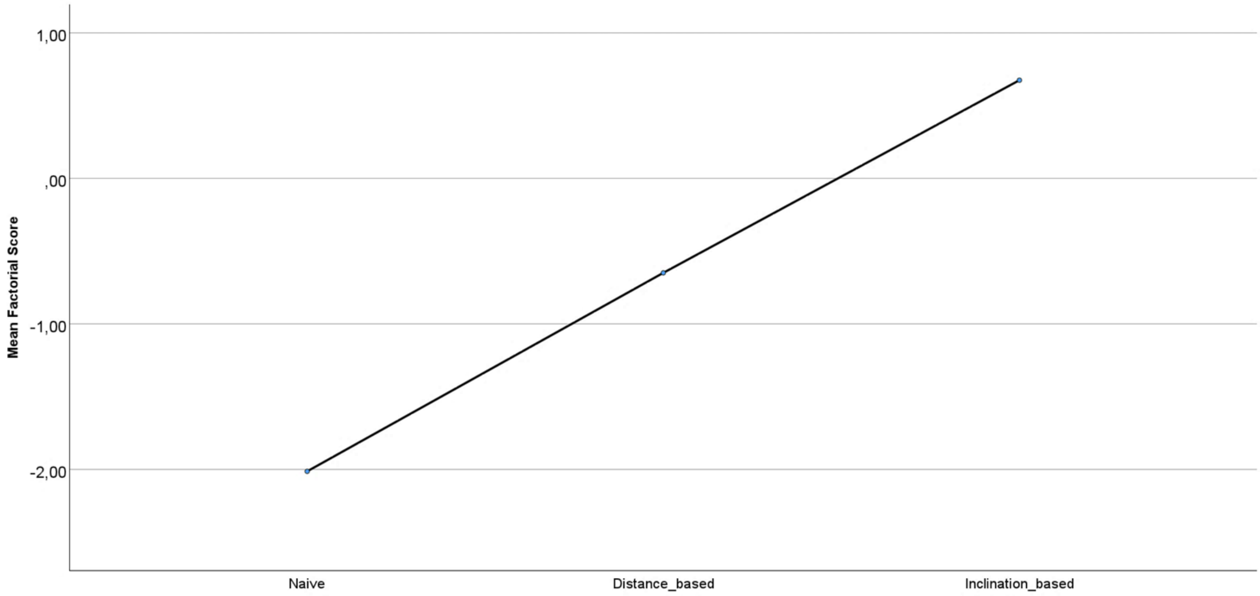


Figure S9. Mean factorial scores of drawings categories

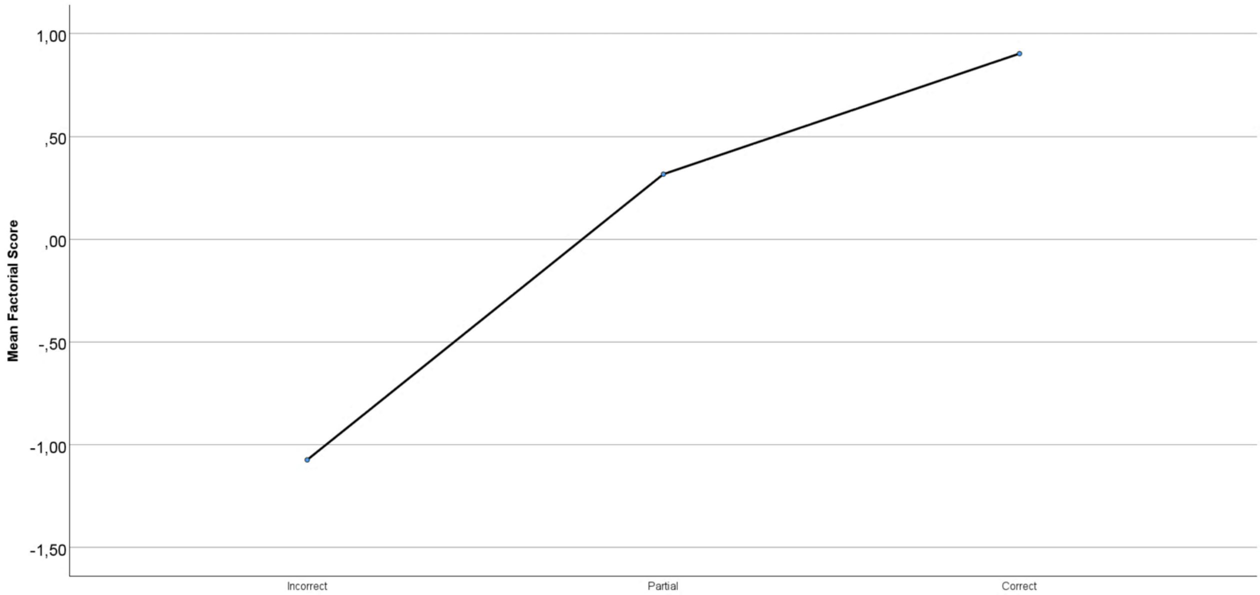


Figure S10. Mean Factorial scores of explanations categories