

Student understanding of the apparent motion of the Sun: Insights from an in-depth interview study

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(Received 12 March 2026; accepted 9 September 2026; published 9 October 2026)

Despite daily observations of the Sun, many students continue to struggle with the mechanisms explaining its apparent motion. Even after formal instruction, students often develop only fragmentary understandings and construct alternative mental models. This study investigates these models in depth to gain genuine insight into the knowledge structures students develop regarding the Sun's apparent motion. We conducted individual task-based think-aloud interviews with 16–18-year-olds in which they articulated their mental models verbally, through drawings and by using three-dimensional materials. These explanations were then analyzed to determine whether the mental models included the essential elements, characteristics, and connections consistent with scientific understanding. The analysis showed that students often described individual aspects of the phenomenon correctly, but rarely provided adequate allocentric explanations. Missing components in their models were frequently supplemented with alternative ideas that clustered around five themes: cardinal directions, distance, orientation of Earth's axis, lines of sight and sunrays, and the orientation of the Sun's orbital plane. These themes, the variety within each, and the implications of our findings are discussed in detail.

DOI: [10.1103/mtbf-vy62](https://doi.org/10.1103/mtbf-vy62)

I. INTRODUCTION

Astronomy has fascinated humans across cultures and throughout history. It is not only an engaging scientific domain; it is also deeply connected to everyday experience: many astronomical phenomena, such as the daily motion of the Sun and the changing seasons, affect everyone. These familiar phenomena often give rise to strong intuitive ideas, making astronomy engaging for many students and a potential gateway science to other STEM fields.

Despite our frequent observations of the Sun and stars and the general knowledge that Earth spins around its axis and revolves around the Sun, research has shown that the apparent motion of the Sun and stars remains difficult to grasp for learners of all ages [1–8]. Even formal

instruction on Earth's rotation and revolution does not guarantee the development of scientifically accepted mental models of celestial motion. Although some aspects may be better understood than others, most students continue to struggle with fundamental concepts, indicating that effectively teaching these phenomena is far from straightforward [3,9].

A key challenge in developing a deep understanding of these astronomical phenomena is that it requires reasoning beyond direct experience, considering large spatial scales, different reference frames, and indirect observations of Earth's rotation and revolution. Astronomy comprises many interrelated concepts with complex causal relations, making it an ideal context for exploring student understanding and (domain-specific) learning processes.

Building on this rationale, Bekaert *et al.* [10] developed and validated a paper-and-pencil questionnaire called the Apparent Motion of Sun and Stars (AMoSS) test. Using a latent class analysis and students' explanations, they identified five mental models of the apparent motion of the Sun and the stars [2,9]. However, their statistical method and students' written explanations were not sufficient to achieve a truly in-depth understanding of the mental models of students.

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The present study aims to address this limitation by adopting an alternative approach: individual, task-based think-aloud interviews incorporating targeted questions and concrete materials aimed at eliciting students' mental models. This paper reports on the findings of this interview study with respect to the content of students' mental models. Section II reviews earlier research on basic astronomical concepts and discusses the role of mental models in science education, while Sec. III describes the methodology of this study. Section IV and V present the results and discussion, respectively.

II. THEORETICAL BACKGROUND

A. Learners' understanding of the Sun's apparent motion

The literature on how learners understand and develop basic astronomical concepts concerning the Earth-Sun system covers a wide spectrum of topics and age groups, ranging from young children's naive ideas about the shape of the Earth [11] and learners' conceptions related to the day and night cycle [1,6,7,12–17], over the origin of the seasons [6,7,13,14,18–22] and (changes in) the Sun's daily path [2,3,6–9,15,16,20,22–26]. Although these studies differ in research methods (interviews, multiple-choice questions with or without written explanations, etc.), as well as in the researched population (elementary school children, secondary school children, high school students, and university students) and the specific aspects that were investigated, in general they all converge on a common conclusion: these basic astronomical phenomena are difficult to grasp for learners across all age groups.

When we specifically consider students' understanding of the Sun's apparent motion, it becomes clear that this topic is in fact highly complex and comprises multiple interrelated aspects. It involves not only describing and explaining the Sun's daily path across the sky (including its culmination height and the directions of sunrise and sunset) but also requires accounting for seasonal and latitudinal variations of this apparent motion. To the best of our knowledge, no previous study has examined all these aspects in an integrated and in-depth manner. Most existing research has instead targeted isolated elements of this phenomenon, for example, by probing whether students know that the Sun cannot be overhead at noon at latitudes that are far from the tropics (e.g., [6,7,13,15,16,20,23,25,26]). Depending on the study, employing different methodologies and involving different age groups, the proportion of correct responses to this “overhead question” varies substantially, ranging from approximately 14%–36%.

A broader perspective was adopted by Plummer [22], who investigated the ideas of first-, third-, and eighth-grade students about the apparent motion of the Sun, Moon, and stars, focusing on how these ideas develop from

elementary to middle school in the absence of targeted instruction. While the results indicated age-related progression in students' ideas, particularly with respect to the Sun's daily motion, no corresponding improvement was found for students understanding of seasonal differences in the Sun's path. To illustrate, many first-grade students believed that the Sun simply rises to the zenith, remains there, and then sets without moving across the sky. Third-grade students more often described a continuous daily path across the sky but believed that sunrise and sunset occur in nearly the same place year-round. Moreover, almost all students, regardless of age, depicted this path as passing through the zenith and rarely indicated seasonal variations in either path length or culmination height.

Similar difficulties have been documented among populations from which a more complete understanding might be expected. Trumper [8], for example, examined preservice elementary and junior high school teachers who had engaged in a series of learning activities targeting their conceptions of astronomical phenomena. Although most participants correctly identified the general location of the Sun's path in the sky and recognized seasonal changes in the Sun's altitude at noon, many still failed to draw correct conclusions regarding the seasonal shift in sunrise and sunset directions.

While these studies provide valuable insights, they do not examine all aspects of apparent solar motion in an integrated and in-depth way. This led Bekaert and colleagues to explicitly do so in their series of studies [2,3,9,10]. Their aim was to identify secondary school students' mental models concerning the apparent motion of the Sun and stars. To achieve this, they developed and validated a new instrument, the AMoSS test. This test consists of 12 multiple-choice items: six addressing different aspects of the Sun's apparent motion and six parallel items addressing the same aspects for the stars, enabling a direct comparison of students' understanding of both apparent celestial motions. The test required students not only to select an answer but also to provide a written justification [10]. In a subsequent study [9], the test was administered to 16–17-year-old secondary school students in Flanders. Despite prior instruction, the results showed that most students held only a rudimentary understanding of the apparent motions of the Sun and stars across different times of day, seasons, and observer locations. In general, students performed better on the Sun items than on the star items. Their explanations suggested a strong reliance on everyday observations or prior knowledge, and they rarely adopted an allocentric perspective when reasoning about the Sun's motion.

Although Bekaert and colleagues aimed to investigate all aspects of apparent motion in an integrated manner, their initial analyses still reported results per aspect. Therefore, in addition, they applied latent class analysis to the multiple-choice responses to identify underlying

patterns in students' thinking. This analysis revealed five distinct classes which, supported by students' written explanations, were interpreted as five mental models. Students in the first three classes demonstrated a relatively accurate understanding of the Sun's apparent motion, but their ideas about the stars differed substantially. Most students assumed that star trails change throughout the year in the same way as the Sun's path, whereas a smaller group believed the opposite: while the Sun's path becomes lower and shorter in winter, star trails become higher and wider. A fourth class was characterized by the belief that the culmination height of both the Sun and stars is proportional to the observer's latitude. A fifth class assumed that the rising and setting positions of the Sun and stars remain fixed—always exactly east and west—regardless of season or observer location. Similar patterns were found in a European comparison involving Belgian, German, Greek, and Italian students [2].

Even though these findings are informative, their methodology imposed important limitations. Because the study relied on a paper-and-pencil questionnaire, students' reasoning could not be probed in depth. Written explanations were often brief or absent, unclear responses could not be followed up, and probing to reveal the underlying understanding of specific mechanisms was not possible. It therefore remains uncertain whether students would be able to articulate more sophisticated, allocentric explanations when explicitly prompted. Moreover, many responses appeared to reflect memorized facts, and the methods used did not allow to determine whether students can genuinely reason with this knowledge or whether they merely reproduce fragmentary understandings derived from observation or from prior instruction. Distinguishing answers based on reproduction of learned explanations from an actual understanding of the phenomena would provide meaningful insight. In addition, latent class analysis, while valuable for identifying patterns in response data and classifying students with similar response patterns in groups, cannot reveal mental models at the level of individual students. Even within classes, there may be meaningful variation among students' reasoning. As a result, although the study made an initial attempt to access students' mental models, the methodological approach allowed only a limited view of their underlying conceptual structures: genuine mental models cannot be identified in this way. These methodological limitations highlight the need for a clearer conceptualization of what we mean by a mental model and how such models can be more meaningfully accessed. We address this in the next subsection II B.

B. Mental models

There are many different descriptions of and approaches to mental models in the literature. In this paper, we will use the term consistently with Greca and Moreira [27] viewing

a mental model as an individual's internal representation of the world. It is created in interaction with this world to reason, solve problems, answer questions, etc. A mental model is based on a person's preexisting knowledge, experiences, and beliefs, and therefore reflects their underlying knowledge structure [11,28]. Based on the ideas of Machamer *et al.* on mechanistic reasoning [29], we argue that a mental model needs to contain the relevant elements of the situation, certain spatial, structural, and dynamic characteristics of these elements, as well as the connections between them.

Mental models can be used to generate explanations and predictions and to develop a deeper understanding of a given phenomenon [1,11,30]. Furthermore, they are dynamic structures that are constructed in a certain situation but can also be adapted or even refuted when new information or experiences conflict with the existing models [11,31,32]. Ideally, these model revisions push the existing mental model toward a more scientifically accurate representation [33].

Because mental models are assumed to reflect an individual's underlying knowledge structure, gaining insight into students' mental models provides an indirect window into how someone understands a given concept or phenomenon. This is especially valuable in the context of education and educational research, where knowledge construction is broadly conceived, from a constructivist perspective, as an active process in which new information is integrated into an existing knowledge network. Whether and how this integration occurs depends at least partly on the structure of that prior knowledge and the beliefs associated with it. It is therefore essential for educators to understand the conceptual foundations on which instruction builds and to identify students' preexisting ideas about the subject matter. Such insight allows instructors to adapt instructional strategies and thereby support more effective learning.

While each learner develops a unique knowledge structure, previous research on mental models and alternative conceptions has shown that certain ideas recur across individuals [11,34]. Identifying these recurring alternative ideas in learners' mental models therefore allows researchers to characterize common patterns in their thinking while still acknowledging individual variation.

Gaining genuine insight into the structure and content of such mental models requires methods that probe students' reasoning in depth, as illustrated by the work of Vosniadou and Brewer [1,11]. In their investigation of children's explanations of the shape of the Earth and the day-night cycle, they conducted detailed, semistructured interviews in which they asked questions and elicited drawings during individual sessions. This approach enabled them to explore students' thinking beyond surface-level responses. In addition to factual questions, they also used so-called generative questions. These are questions about

phenomena that cannot be directly observed and for which no explicit instruction has been provided. Such questions compel learners to activate and reason with their mental models rather than merely relying on memorized information. Given our aim to investigate students' mental models of the Sun's apparent motion in an integrated and in-depth manner, we included generative questions among the strategies used in this study.

III. METHODOLOGY

To gain a more in-depth understanding of students' explanations and, consequently, their underlying mental models of the apparent motion of the Sun, we conducted individual task-based think-aloud interviews. Using this methodology, we actively engaged students in constructing and reasoning with mental models, which allowed us to move beyond merely eliciting isolated statements or factual responses. Students were encouraged to externalize their reasoning processes as explicitly as possible while engaging with the tasks, thereby providing richer insight into their mental models.

A. Participants

We interviewed 22 students aged 16–18 years from the 11th and 12th grades at three secondary schools in Flanders, Belgium. All participants had received formal instruction on Earth's rotation and revolution as part of their geography curriculum prior to the interviews and had completed a formal examination on the topic.

Schools were recruited through invitations sent to school principals of secondary schools located near the first author's place of residence. Three schools agreed to participate and allowed students to take part during school hours. The first author informed the geography teachers and their students about the study and invited volunteers to participate. Interested students could register for participation and indicate whether they preferred to be interviewed during or after school hours. Participation in the study was voluntary and did not affect students' school grades.

Prior to participation, all students provided informed consent. According to Flemish regulations, participants aged 16 years and older may provide informed consent themselves. The study was approved by the Social and Societal Ethics Committee (SMEC), approval number G-2025-8995-R2(MAR).

B. Interview

We conducted individual interviews at the students' schools and audio- and video-recorded them. The interviews on average lasted approximately 55 min. They explored five core aspects of the apparent motion of the

Sun, corresponding to five Sun items from the AMoSS instrument [10]:

- (A) the daily motion, including the direction of sunrise and sunset;
- (B) seasonal changes in culmination height;
- (C) seasonal changes in the direction of sunrise and sunset;
- (D) latitude-dependent variations in culmination height;
- (E) latitude-dependent variations in the directions of sunrise and sunset.

Although the interview also included a question on the explanation of the seasons, we do not report on these answers in this paper.

For each of these aspects, the interview followed a fixed two-step structure. First, students were asked the corresponding AMoSS question, allowing us to assess whether they could correctly describe the observable phenomenon [10]. The complete wording of these questions is provided in Appendix A. Second, students were asked to explain the phenomenon, with a particular focus on underlying allocentric reasoning. To encourage such reasoning, students were explicitly prompted to move beyond Earth-based descriptions and explain the phenomena in terms of the spatial relations and motions of the Earth and Sun, using verbal explanations, gestures, drawings, and three-dimensional materials such as spheres. While the thematic structure and starting questions were fixed, follow-up questions depending on students' responses were used to elicit in-depth explanations. To avoid that students explained the phenomena by just "memorized explanations," we systematically included generative questions [1,11] to probe whether students recognized critical features of the underlying model, e.g., by asking how a phenomenon would be impacted if the Earth were not spherical but cylindrical. An overview of the generative questions and the detailed interview protocol for aspect B (seasonal changes in culmination height) are provided in Appendix B and C.

The main focus of this study is on students' explanations of phenomena that can be observed on Earth, rather than on describing these Earth-based observations. By eliciting allocentric reasoning and combining students' verbal explanations with nonverbal representations, we aimed to obtain a clear picture of students' mental models by making underlying assumptions as explicit as possible, thereby minimizing the need for post hoc interpretation.

Similar materials have previously been used by Atwood and Atwood [19] in their study of preservice teachers' understanding of the causes of the seasons. They found substantial inconsistencies between participants' verbal explanations and their manipulations of the materials, which illustrates the importance of probing learners' explanations in depth, as surface-level verbal responses

may mask significant gaps or inconsistencies in underlying understanding. Therefore, we additionally and explicitly asked students to reflect on whether, and how, their verbal expressions could be linked to their nonverbal representations.

All interview recordings, including students' verbal explanations as well as nonverbal expressions such as gestures, drawings, and manipulations of materials, were transcribed verbatim for analysis.

C. Analysis

To determine whether students' expressions reflect a mental model of the Sun's apparent motion that is consistent with the scientific model, we developed a coding scheme. We therefore decomposed the scientific model into its constituent elements, the characteristics of these elements, and the connections between them, consistent with the ideas of Machamer *et al.* [29]. We used this coding scheme to assess whether essential components were present in students' mental models, whether alternative ideas were expressed, and/or whether any critical features were missing. The coding scheme was organized per aspect (A–E) and consisted of four columns that served as a checklist. Each component was coded as correctly stated, incorrectly stated, not mentioned, or unclear. When students expressed changing ideas during the interview, the direction of change and the corresponding turning point were documented. The columns were:

- **Elements** (Earth, Sun, observer)
- **Spatial, structural, and dynamic characteristics of the elements** (e.g., Earth: has an axis; rotates on that axis; Sun: is very large; emits light and sunrays; observer: defines a horizon plane; defines cardinal directions)
- **Connections between elements and their characteristics** (e.g., the observer looks at the Sun at a certain angle; this angle depends on the orientation of the observer-Sun system and thus on latitude)
- **Scientific explanation**, describing the necessary features of a student's explanation

The complete coding scheme for aspect B is provided in Appendix D.

Using this coding scheme, we first analyzed the students' explanations for the different aspects of the apparent motion (A–E) separately. In a next step, we analyzed their responses to the generative questions using a modified version of the scheme, specifically adapted to account for the features explicitly probed by these questions. This modified version incorporated additional characteristics and connections relevant to the hypothetical scenarios, while omitting features that were no longer relevant. The modified coding scheme was used exclusively for the generative questions,

whereas the original coding scheme was retained for the regular questions (A–E).

To illustrate, for generative question 3, which probes the effect of a tilted axis, the characteristic “*tilted relative to the ecliptic plane*” was replaced by “*perpendicular to the ecliptic plane*.” Furthermore, the modified scheme included additional connections, such as the assumption that the daily path of the Sun remains identical throughout the year for a given location, that day and night each last approximately 12 h, and that sunrise and sunset always occur in the east and west, respectively.

Analyzing the responses to the generative questions therefore allowed us to identify implicit assumptions in students' earlier responses more clearly. To draw conclusions at the level of individual students, we combined the analyses of the regular and generative questions.

All responses were coded by the first author using the coding scheme described above. To establish interrater reliability, a second member of the research team independently coded approximately one-eighth of the dataset. Interrater agreement across all coding categories was substantial, with a percentage agreement of 88% and a Cohen's kappa of 0.794 ($p < 0.001$).

Our analysis showed that students' reasoning could be flawed in many ways. Many students lacked certain essential components and/or included alternative components in their explanations. However, our analysis also revealed that these difficulties could be attributed to a number of overarching themes that recurred across different aspects of the apparent motion and across multiple students. These themes are discussed in detail in Sec. IV B.

IV. RESULTS

The data provide insight into how students describe observable astronomical phenomena as well as how they explain them. Students' descriptions—discussed in Sec. IV A—primarily serve as important background against which students' explanations can be interpreted and contrasted, and they allow comparison with previous findings. The primary focus of this study, however, lies on students' explanations, reported in Sec. IV B, as these reveal their understanding of the underlying mechanisms.

A. Students' descriptions of the observable phenomena

We first asked students questions related to the description of the following phenomena as observed from Earth: (A) the daily motion of the Sun, including the directions of sunrise and sunset; (B) seasonal changes in culmination height; (C) seasonal changes in the directions of sunrise and sunset; (D) latitude-dependent variations in culmination height; and (E) latitude-dependent variations in the directions of sunrise and sunset. These results are summarized in Table I.

TABLE I. Summary of students' responses to the AMoSS questions (A–E), including the number of correct final answers per question (maximum = 22), the number of answer revisions during reasoning, and the percentage of those revisions that resulted in a correct answer.

Question	Observable phenomenon	Correct answers	Answer revisions	% correct revisions
A	Daily motion	21	0	0%
B	Seasonal changes in culmination height (CH)	21	4	75%
C	Seasonal changes in direction of sunrise and sunset (R and S)	12	13	54%
D	Latitude-dependent changes in CH	17	9	56%
E	Latitude-dependent changes in direction of R and S	14	6	67%
Total		85	32	59%

We found that most students were aware of these phenomena: 17 of the 22 interviewed students answered at least four out of five questions correctly, with six students answering all five questions correctly. In line with the findings of Bekaert *et al.* [2,3,9], certain aspects of apparent motion proved to be more challenging for students.

Twenty-one participants correctly described that the Sun appears to move along an arc from east to west (question A). One student repeatedly confused east and west during his explanation and therefore arrived at an incorrect conclusion.

Students experienced greater difficulty answering the questions addressing the direction of sunrise and sunset (questions C and E). Not only did fewer students answer correctly (12 out of 22 for the yearly changes and 14 out of 22 for the latitude-dependent changes), they also revised their answer quite frequently during reasoning (i.e., 13 and 6 students, respectively). One student maintained that the Sun always rises exactly in the east and sets exactly in the west, regardless of location in the northern hemisphere, and that this direction does not change over the course of the year. At least two other students initially expressed similar views regarding the latitude-dependent variations in sunrise and sunset directions, but revised their answers during the interview.

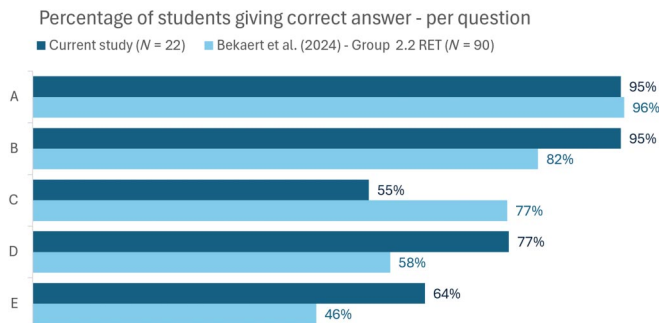


FIG. 1. Percentage of correct responses for each AMoSS question (A–E) in the present study compared with the retention results reported by Bekaert *et al.* [3] for the group that completed a learning module on the AMoSS.

Regarding the yearly changes in the Sun's culmination height (question B), 21 students provided the correct answer, with one student ultimately concluding that, in summer, the Sun's highest point in the sky would shift somewhat toward the west but would remain at the same altitude. Nevertheless, several students (4 out of 22) expressed uncertainty and changed their answer while reasoning. Notably, five students adjusted their responses to the B and/or C questions after being asked to draw the Sun's daily path in June, indicating that this suggestion helped them to explicitly connect changes in culmination height with changes in the direction of sunrise and sunset.

Finally, the question concerning latitude-dependent changes in the Sun's culmination height (question D) was answered correctly by 17 of the 22 students. As with other questions, uncertainty was common: nine students revised their responses during the reasoning process.

Overall, the results indicate that several students provided more or less correct answers to most questions at some point in the interview but were not always confident in their observations and predictions regarding the Sun's apparent motion. Many students revised their answers—sometimes multiple times—during the reasoning process. In total, 17 students changed at least one of their responses, and 9 students revised two or more answers during the interview. As shown in Table I, some of these revisions resulted in correct conclusions, whereas others did not.

The distribution of correct responses in the present study largely follows the trend reported by Bekaert *et al.* [3], as shown in Fig. 1. Except for question A—which was answered almost perfectly in both studies—and question C (concerning seasonal changes in the direction of sunrise and sunset), the numbers of correct responses are somewhat higher in our study.

B. Students' explanations of the observable phenomena and their underlying mental models

While many students could correctly describe multiple observable phenomena, further probing for explanations often revealed substantial difficulties, even in cases where

the students initially provided the correct answer. Providing a complete and coherent explanation proved to be a very challenging task. Indeed, none of the participating students were able to explain all aspects of the apparent motion of the Sun based on a fully scientifically consistent model.

Analyzing the interviews indicated that students' mental models were frequently incomplete: essential components were missing, and these "gaps" were often accompanied by the activation of alternative ideas. We were able to organize the difficulties students encountered into a limited set of recurring themes. Identified through our coding framework, these themes group together related alternative ideas and recurred across multiple aspects of the phenomenon, suggesting systematic misunderstandings in students' underlying mental models.

In Sec. IV B 1, we describe each of the identified themes in detail and discuss how they hinder students' explanations of different aspects of the Sun's apparent motion, illustrating each theme with representative student quotes. As the interviews were conducted in Dutch, we translated all quoted excerpts to English. We want to stress that the analysis focuses on broader categories of recurrent explanatory ideas rather than on isolated or idiosyncratic responses. Finally, Sec. IV B 2 provides an overview of students' understanding of different aspects of apparent motion.

1. Identified themes of difficulties

Theme 1: The cardinal directions.

Definition of observer-based coordinate system and cardinal directions. To describe where they see the Sun at its highest point, or in which direction they observe sunrise and sunset, students need a well-defined reference frame: an observer-based coordinate system that specifies directions along the horizon and angles above it.

This reference frame is typically defined starting from the horizon plane—an imaginary plane on which the observer stands, tangent to Earth's surface and separating the visible half of the sky from the part below the horizon. On this plane, north is defined as the direction toward Earth's geographic North Pole, with east, south, and west arranged in their conventional clockwise order. The north-south line on the horizon plane is aligned with the observer's local meridian.

A celestial object's position (in our interviews: the Sun's position) at a given time is specified by two coordinates. The first is its direction on the horizon plane with respect to the cardinal directions (north-east-south-west). The second is its altitude, defined as the angle between the horizon plane and the observer's line of sight. An altitude of 0° corresponds to the horizon, and 90° corresponds to the zenith. Together, these two coordinates uniquely determine the object's position in the observer-based

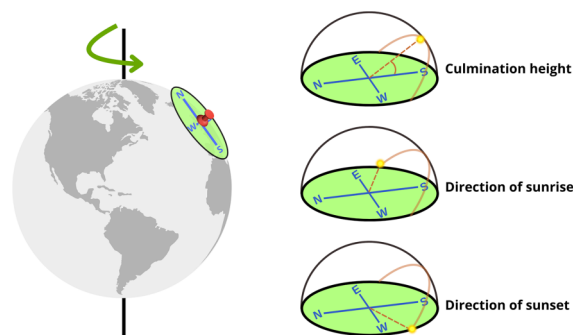


FIG. 2. Illustration of a horizon plane defined on Earth, with the red pin indicating the observer's position. Cardinal directions are shown on the observer's horizon plane (green plane). The three diagrams on the right illustrate the use of the observer-based coordinate system, with the orange line representing the Sun's daily path in winter. The top diagram shows how altitude determines the Sun's culmination height, while the two lower diagrams show how cardinal directions are used to express the directions of sunrise and sunset.

coordinate system at a given time (Fig. 2). The culmination height (questions B and D) corresponds to altitude in this system, while directions of rise and set (questions C and E) are expressed in terms of cardinal directions on the horizon plane.

Student difficulties with cardinal directions. Correctly defining the cardinal directions is important to explain in what direction the Sun rises or sets and how these directions change throughout the year and with different latitudes. However, many students struggled with this definition, making it a recurring theme in responses to questions A, C, and E. In what follows, we describe how both difficulties in defining the cardinal directions and in using the defined coordinate system hindered students' reasoning.

Most students knew the cardinal directions (north-east-south-west) by heart, and all but one recognized that the Sun rises in the east and sets in the west. They also understood that the Sun's daily motion is apparent and results from Earth's rotation. However, explaining why sunrise occurs in the east and sunset in the west—and whether and how these directions vary throughout the year and with latitude—proved substantially more challenging: of the 22 participating students, 21 experienced difficulties in defining and/or applying the cardinal directions on a three-dimensional model when answering at least one interview question. When working with the physical materials, students were generally able to illustrate the alternation of day and night and to identify the rotational positions corresponding to sunrise and sunset. However, when asked to use the model to explain why sunrise occurs in the east and sunset in the west, only seven students succeeded. Many struggled with correctly defining the cardinal directions on the 3D

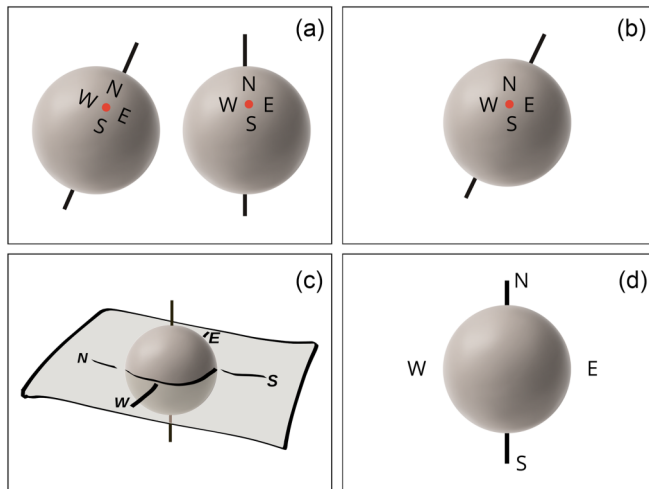


FIG. 3. Schematic representations of how students define cardinal directions on a 3D Earth model: (a) directions defined without using the horizon plane, but still valid; (b) directions defined without the horizon plane and without adjusting for a tilted axis; (c) cardinal directions defined in a horizontal plane around the Earth; and (d) cardinal directions defined around the Earth, with the North and South Poles taken as north and south.

model itself—that is, they had difficulty mapping east and west onto the physical representation and using these directions in their explanations.

As mentioned in the previous paragraph, everything starts with a horizon plane on which the cardinal directions are defined. However, most students did not explicitly refer to such a plane in their explanations. Still, if they placed the cardinal directions correctly around the observer, aligned with the meridians, their model could remain valid [see Fig. 3(a)]. In practice, only a small number of students did so successfully. Several recurring difficulties emerged.

First, more than one-third of the students experienced substantial difficulties in adopting the observer’s perspective while using a sphere to represent Earth. When prompted to represent the observer as a pin on the sphere and to define north, east, south, and west with the materials, these students frequently expressed uncertainty, as illustrated by the following excerpts and Fig. 4:

Student 1: “Wow, this is really difficult with a little figure. Because on a map, east is usually on that side [points to her right]. But if I’m standing here now, I don’t know...”

Student 14, while turning the observer on the opposite side to where she is sitting: “North, east, south, west. So then it’s the other way around [sigh]. This is too hard, I think. North, east, south, west, I would say.”

Even students who could verbally state how the cardinal directions should be defined on a sphere did not always



FIG. 4. Screenshot of student 14 while identifying the cardinal directions using the 3D materials. Although the student correctly defined the cardinal directions relative to her own position, east and west were defined incorrectly when the pin was located on the side opposite to where they were sitting.

succeed in applying this knowledge consistently. Several students correctly aligned north and south with the Earth’s axis but interchanged east and west when the observer was positioned on their opposite side of the globe, as is demonstrated in Figs. 4 and 5 and in the following excerpts:

Student 12, in response to the question “How do you determine where east is?”: “You look from my position—you look toward the north of the Earth. And then you have east, south, and west.” [shows the cardinal directions correctly. However, when the Earth is rotated around its axis—placing the pin (the observer) at the opposite side—east and west are no longer demonstrated correctly]

Student 19, in response to the question “Now show me how you define east, south,

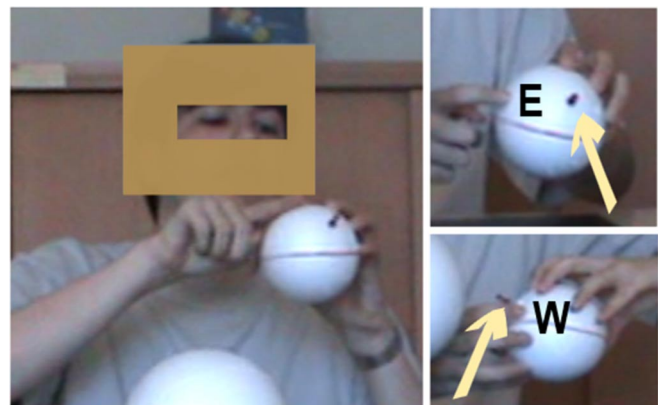


FIG. 5. Screenshots of student 19, explaining how the cardinal directions should be defined on the sphere, with the arrows pointing out the location of the observer. They literally tried to look from the perspective of the observer.

and west”: “I look toward the Sun. Wait. I already know south—the north and south are easy. That’s just the North Pole and the South Pole. And then I just look from my own position [the pin], because...In your book [textbook], it’s of course reversed. But that’s because you’re looking down on the Earth. And then I think: How do I see it? So I look like, okay, when I look toward the Sun from here, from this little point, as if I’m really looking at it, it seems as if it is now in the east [points to the left of the pin from the interviewer’s point of view]. And now it seems as if it is in the west [points to the right of the pin].”

Second, nine students did not use an observer-based coordinate system. Instead, most of these students defined the cardinal directions with respect to the Earth as a whole, implicitly placing the Earth at the center of their reference frame rather than the observer. Several students placed north, east, south, and west at fixed locations around the Earth in a horizontal plane [Figs. 3(c), 6, 7, and 8]. Others defined cardinal directions relative to the Earth’s poles, with north taken as “on top of” the Earth or “at the North Pole” and south as “at the bottom” or “at the South Pole” [Figs. 3(d), 9, and 10]. We illustrate some of these approaches with quotes and screenshots. These examples reveal that, despite similarities, students’ reasoning was based on different underlying assumptions. Furthermore,

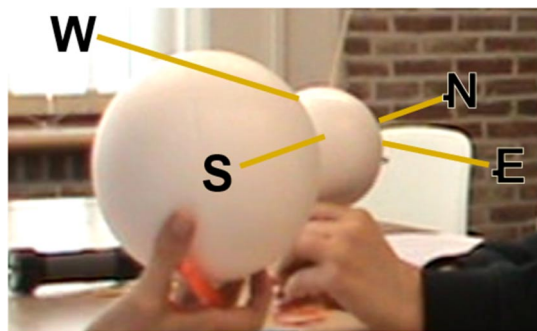


FIG. 6. Screenshot of student 3, defining the cardinal directions in a horizontal plane, with the Earth (and not the observer) in the center and south as the direction of the Sun at noon.

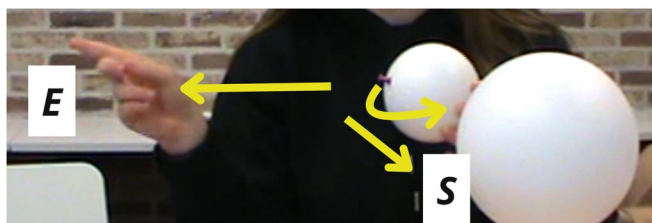


FIG. 7. Screenshot of student 8, defining the cardinal directions in a horizontal plane, with the Earth in the center and east as the direction of the observer when the Sun rises.

students did not always consistently use the same coordinate system throughout the entire interview, as illustrated by the quotes and screenshots of student 21 (Figs. 8 and 9).

Student 3, in response to the question of why they defined south to the left of their Earth model: “South, north, west, east [indicates four directions, with the Sun corresponding to the

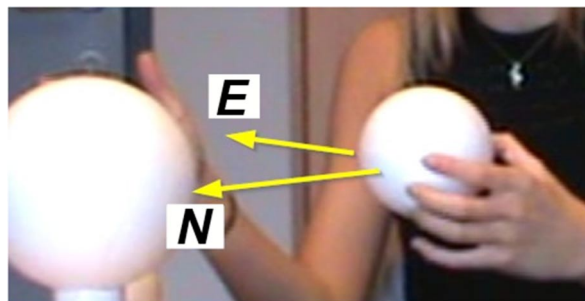


FIG. 8. Screenshot of student 21 defining the cardinal directions in a horizontal plane, with the Earth at the center, north defined as the direction of the Sun at noon, and east defined as the direction of the observer at sunset.

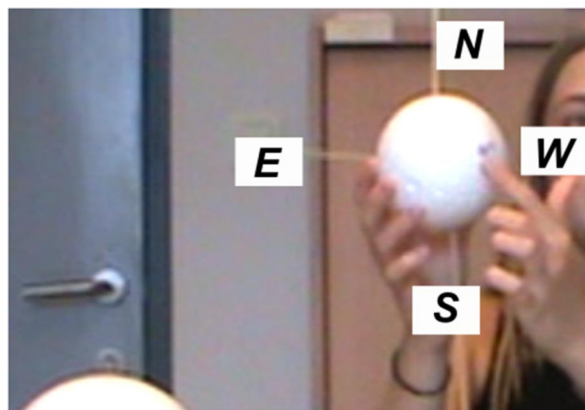


FIG. 9. Screenshot of student 21, defining the cardinal directions around the Earth but now based on the poles.

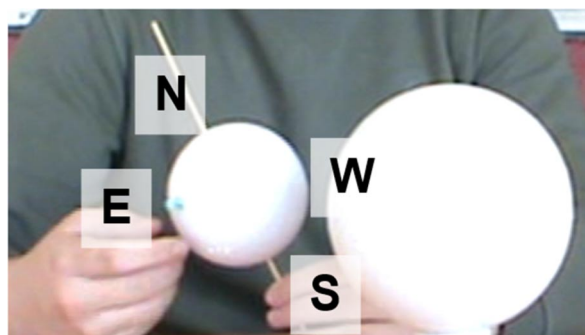


FIG. 10. Screenshot of student 11, defining the cardinal directions around the Earth, based on the poles.

south] ...Because the Sun is always in the south and never in the north.”

Student 8, in response to the question “Where is sunrise?”: [Rotates the Earth counterclockwise until the observer (pin) is at the moment of sunrise and points to the right] “East...” “**And when you rotate further?**” [Rotates counterclockwise, until the pin is oriented toward the Sun, points toward the Sun] “South.”

Student 21, in response to: “You say that the Sun rises in the west. Can you tell that this is the west (using the material)?” “No...Yes, I think it does rise in the west...So it then starts in the west, and at the highest point of the day the Sun is actually in the north [shows the Earth with the pin directly toward the Sun]...And then it keeps turning further and further [rotates the Earth further around its axis and simultaneously indicates, with an arc-shaped movement of her hand, that the Sun moves across the observer’s view]. And then it goes along with the rotation. Or, well, we rotate. And then it goes toward the east [rotates the Earth further around its axis], and then eventually it sets.”

Same student, student 21, a few minutes later when the interviewer asked “How would you define your cardinal directions then?” “So this is north. And then east. And then south [places three sticks on the Earth model, one for each direction]. And the pin is then in the west. That’s how I would...” “**And north and south are actually?**” “Yes, the poles, yes.” [points to the North Pole]

Student 11, in response to the question “How do you define your cardinal directions?”: “Here is east and then here is west” [points to the right and then to the left side of the Earth]. “**And where are your north and south?**” “North is on top and south is on the bottom” [points to the North and South Poles].

Third, besides struggling with defining the cardinal directions, more than half of the students experienced difficulties in inferring the directions of sunrise and sunset, and thus in using their coordinate system. These were often the same students who had incorrectly defined their cardinal directions, but not always. In many cases, students interpreted the position or orientation of the pin relative to their coordinate system at the moment of sunset as the direction of sunset (Fig. 12). This led to statements such as those from student 3 (screenshot in Fig. 11), who exemplifies schematic representation (a) in Fig. 12.

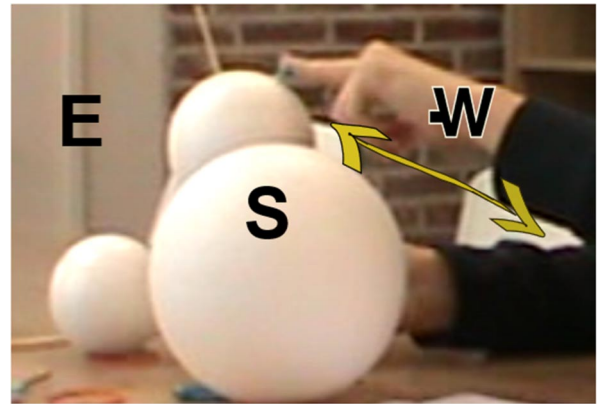


FIG. 11. Screenshot of student 3, illustrating how they inferred that the Sun sets more toward the southwest in winter.

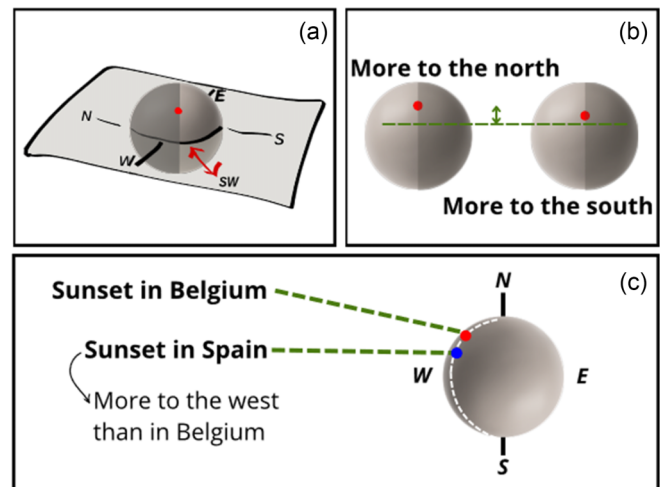


FIG. 12. Schematic representation of three ways in which the position of the pin was used to infer the direction of sunset. In panels (a) and (c), the location of the pin relative to an Earth-based coordinate system is interpreted as indicating the direction of sunset; in panel (c), the white dashed line represents the border between day and night. In panel (b), the direction of sunset is inferred from the pin’s relative position on the Earth at the moment of sunset.

Student 3: “Here you have it...If it is like this...[tilts the axis away from the Sun] So this is December, it [the Sun] is setting. And here it sets, so that is approximately in the southwest. Whereas if it is like this in September and it rotates to here, [puts the axis upright for September and rotates toward the moment of sunset] then it sets more in the west. Because then it is more toward this side when it sets [points to the west in her coordinate system]. And in December it is more toward this side [points toward the southwest in their coordinate system].”

There were also students who did not use their previously defined coordinate system and instead relied on the



FIG. 13. Screenshot of student 15 attempting to infer why the Sun appears to set in different directions in winter and summer. The student forms the daily arc of the Sun with their thumb and index finger and positions it above the observer. In doing so, they also (maybe unintentionally) change the angle of incidence.

position of the pin on the Earth to explain changes in the direction of sunrise and sunset throughout the year. Due to the tilted axis, the pin appeared to be positioned slightly higher on the Earth at some times and lower at others. Students often did not use the words “higher” and “north” precisely, and a higher pin was sometimes interpreted as meaning that the Sun sets more toward the north [see Fig. 12(b)]. To illustrate, the reasoning (and screenshot in Fig. 13) of student 15:

Student 15: “Yes, like this [tilts the Earth’s axis away from the Sun]... The sunrays are like this [shows an arc with thumb and index finger]. Then it comes here, more directed toward the North; and when it is like this [tilts the Earth’s axis toward the Sun], it is more directed toward the South.”

Additionally, some students did attempt to use a correctly defined coordinate system but were unable to do so successfully due to errors related to the properties of lines of sight and/or sunrays: they interpreted directions relative to the cardinal directions as slanted upward or downward rather than horizontal. We consider this difficulty as an expression of students’ failure to take the actual sizes and distances in the Sun-Earth system into account. In this sense, it represents an indirect consequence of students’ broader difficulties with size and distance (see the next section for the issues students experience with distances).

Finally, for some students, it remains unclear how they defined and used their coordinate system. This is primarily because the statements they made about the direction of sunrise and sunset while interacting with the material seem to conflict with what we, as researchers, could observe and infer from the model.

Theme 2: Distance.

Distances in the solar system. The spatial scales of the solar system are highly nonintuitive. The Earth is more than 100 times smaller than the Sun, and the distance between the Earth and the Sun is quite large compared to the sizes of both bodies. As a result, sunrays reaching the

Earth can be considered parallel. In addition, because of the very small eccentricity, the Earth’s orbit around the Sun can be approximated as circular.

These characteristics are essential for correct reasoning about the apparent motion of the Sun. Treating solar rays as parallel underlies explanations of the Sun’s changing culmination height (questions B and D) and is needed for correct reasoning about the direction of sunrise and sunset (questions C and E). Similarly, approximating the Earth’s orbit as circular allows seasonal changes in the solar path to be attributed to Earth’s axial tilt and revolution rather than to variations in Earth-Sun distance (questions B and C).

Part of the challenge for students is that these huge distances and spatial relations cannot easily be represented correctly, certainly not with the three-dimensional materials included in the interviews. However, correct reasoning about the Sun’s apparent motion implicitly depends on awareness of these assumptions. In the next paragraphs, we describe how incorrect ideas on distances directly influence students’ explanation of the apparent motion. The indirect influence of distance-related difficulties is addressed in the section on sunrays and lines of sight.

Student explanation of apparent motion based on distance ideas. It is well known that many students believe the Earth’s orbit around the Sun is highly elliptical. This incorrect idea underlies one of the so-called “distance models” for explaining the seasons and is well documented in the literature [6,7,14,19]. In our study, we found that this distance idea also emerges in students’ explanations of apparent motion, both for the seasonal variations in culmination height and, to a lesser extent, for the seasonal variations in the direction of sunrise and sunset.

Thirteen students considered distance to be an important factor in their reasoning for at least one aspect of apparent motion. More than one-third of these students reasoned that the Earth’s varying distance to the Sun influences how high the Sun appears in the sky (question B), although the specific underlying assumptions and the nature of this relationship differ among students. Some students (correctly) believed the Sun is farther from the Earth in summer, while others believed it is closest during that season. Among those who invoked distance, some (like student 9) argued that the Sun appears higher when it is closer, whereas others (like student 2) claimed it appears lower when it is closer.

Student 2, in response to the question why they think the Sun is lower on June 10 than on January 10: “The Earth revolves around the Sun [Takes the Earth model and quickly rotates it around the Sun without paying attention to the axis]. And on June 10, around that period, it is a little closer to the Sun. And in January it is farther

away, so the Sun is farther ...When the Earth is farther from the Sun, so around January 10, then the Sun seems to be higher... Yes, for example, if we are here [holds Earth far from the Sun with upright axis], then from here the Sun seems higher [Brings the Earth, with upright axis, closer to the Sun]. And if we are closer, then it seems closer to us. So then it seems to be lower.”

Student 9, in response to the question why they think the Sun is higher on June 10 than on January 10: “Because the Earth is closer to the Sun then...[moves hand toward the Sun] It [the Sun] revolves [traces an elliptical orbit with the Earth around the Sun]. And in summer it is closer to the Sun than in winter. Here you see it lower [holds the Earth at 6 o’clock, slightly farther from the Sun; winter]. And here, yes, higher, because it is so close [moves the Earth to 9 o’clock, quite close to the Sun; summer].”

Still others, like student 11, linked differences in distance to changes in the angle of incidence or in solar illumination, and from there to variations in day length, which they then in a next step connected to differences in culmination height.

Student 11, in response to the question why they think the Sun is higher on June 10: “Because we don’t move in a perfect circle, the Sun also hits the Earth a bit differently...at some point it will be closer. At other times it will be farther away...But I don’t know exactly when it does which [Takes the Earth model; places it closer to the Sun at 6 o’clock and farther at 8 o’clock; later traces an elliptical orbit with the Sun at one of the foci.] ...Yes, during winter it will definitely be closer, and in summer farther away... Because then you have more time that the Sun hits [days are longer]...Or was it the other way around? One of those two...I don’t remember exactly. But no, it’s because it is closer, then it’s...Or farther away, then it’s longer light and stuff outside. Yes, because it also hits differently, but I don’t remember exactly how that was.” **“You assume it is higher in Summer, should the Sun then be closer or farther?”** “I would say farther. Yes, farther, I think—that seems most logical.”

Approximately one-third of the students who referred to distance to explain the seasonal variations in the Sun’s culmination height also reasoned that variations in the Earth-Sun distance underlie seasonal changes in the direction of sunrise and sunset (question C), illustrated by the following excerpt:

Student 2: “Because then we are moving farther away from the Sun again. Which makes it seem to go more toward the north rather than toward the south... so now [in September] the Earth is about this far. And when it becomes December, the distance from the Sun to the Earth becomes a bit larger [moves the Earth about one-fifth of its orbit, the distance between Sun and Earth increases]. Which makes it seem to shift toward the north. It seems to set more toward the north than toward the south [points north of the pin].”

Not only the assumed shape of the Earth’s orbit gave rise to distance-based explanations. For some students, the tilted axis of the Earth and/or the Earth’s spherical shape also became a source of perceived distance variations. These students then attempted to use such variations especially to explain latitude-dependent differences in culmination height (question D), as is illustrated by the excerpt and screenshot (Fig. 14) of student 4. Although several students recognized during their reasoning that this explanation could not be correct, it was nevertheless an idea they initially—perhaps intuitively—put forward.

Student 4, in response to whether they can explain why the Sun’s culmination height is higher in Spain than in Belgium: “If we look like this, then it [Spain] is closer to the Sun than when we [Belgium] are here [holds the Earth with its axis pointing away from the Sun. Points from Spain to the Sun and then from Belgium to the Sun—see Fig. 14]. That is my explanation.”

All these students explicitly identified distance as the explanatory factor for the observed difference in culmination height, meaning that distance played a direct role in their explanatory models. In contrast, there are students who did not explicitly cite distance as a causal factor. However, they failed to apply the assumptions mentioned

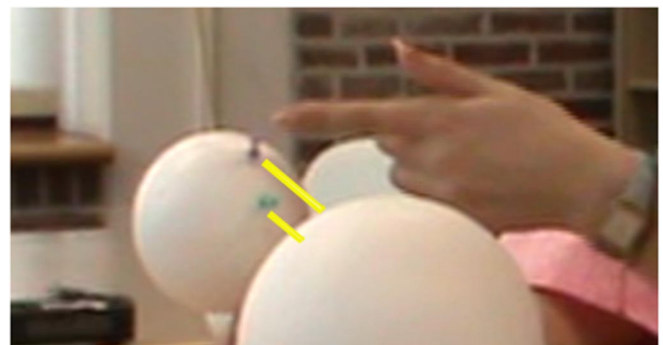


FIG. 14. Screenshot from the interview with student 4, illustrating a distance-based explanation in which differences in the Sun’s culmination height between Belgium and Spain are attributed to differences in distance to the Sun.

earlier—namely, that the Sun is very far away, and that its rays therefore should reach Earth in parallel (or, equivalently, that observers' lines of sight at different latitudes should be drawn parallel). Therefore, they arrived at incorrect conclusions when modeling with materials or making drawings. For these students, distance thus played an indirect role in their reasoning. This indirect role is examined further in the paragraph on sunrays and lines of sight.

Theme 3: Orientation of the Earth's axis.

Earth's axis is tilted with respect to the ecliptic plane. The Earth rotates around its axis in one day and revolves around the Sun in one year. The axis of the Earth is tilted relative to the plane of revolution (ecliptic plane), the angle between the axis and the normal to the ecliptic being 23.5° . This orientation of the Earth's axis remains constant during the yearly revolution.

The fixed tilt of the Earth's axis is vital for explaining the Sun's apparent motion. It causes seasonal variations in the Sun's path (see questions B and C), the seasons themselves, and affects rise and set directions at different latitudes (question E).

Student difficulties related to Earth's tilted axis. Although the axial tilt is important, students struggled to include it effectively in their explanations. This difficulty is well documented in the context of explaining the seasons as temperature differences (e.g., [7,19]). Far less attention has been paid to how students use axial tilt when explaining the Sun's apparent motion. Plummer and Maynard [24] show that, while students frequently mention the Earth's tilt, they rarely coordinate it with changes in culmination height or sunrise and sunset positions.

All students in our study noted that the Earth has a tilted orientation. However, for three of them, this was not directly or solely linked to the Earth's axis; instead, they included an inclined plane of revolution in their mental model. We consider this a separate theme and will discuss it further in the subsection on an inclined orbital plane.

As for the axial tilt itself, while demonstrating the Earth's revolution using the three-dimensional materials, 18 students experienced difficulties representing the orbit and, at some point during the interview, indicated that the Earth's axial tilt changes over the course of the year. This large group comprised multiple types of ideas. We describe these ideas and visualize some of them in Fig. 15.

Some students simply were not aware that they were showing a tilt change. They demonstrated the Earth's revolution without considering the axial tilt. The orientation of the axis that they showed on one side of the Sun differed from the orientation on the other side of the Sun, but they did not realize [Fig. 15(a)]. Some of them later noticed the inconsistency and adapted the orientation of the Earth's axis at different points in the orbit. These adaptations varied: some resulted correctly in a revolution with a tilted but stable axis (e.g., student 1), while others

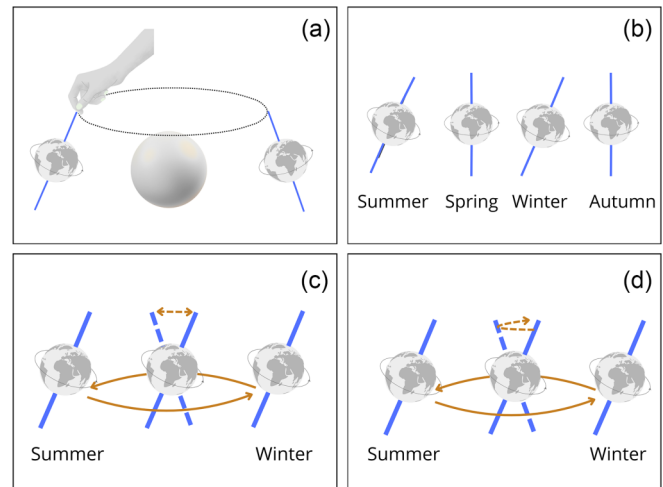


FIG. 15. Schematic representations of demonstrated alternative ideas concerning the orientation of the Earth's axis. (a) Unintentional tilt change. (b) Vertical axis in spring and autumn. (c) Oscillating axis. (d) Oscillating axis with possible rotational component.

recognized they were unable to show the entire revolution, and for the remainder of the interview only demonstrated the axis' orientations for the extreme positions in the revolution: winter and summer (e.g., student 15).

Student 1, while trying to show the revolution of the Earth around the Sun:

"Hmm, I'm really starting to doubt more and more how this works. Eventually—wait—doesn't it actually rotate like this [starts to flip the axis]? Because my North needs to move away from [the Sun]... But I think—I don't know if the Earth actually moves like that [flips the axis back and forth, like in Fig. 15(c)]... Yes, that seems a bit strange, that it does that. So I don't know how my stick [axis] should go... Because here it should be like this [shows axis in summer orientation]. But here it should be like this [places the Earth on the other side of the Sun, axis in winter orientation]. So isn't that just the same? Yes, that's just the same. It just looks really weird when I'm turning it." (laughs)

Student 15, while trying to demonstrate the difference in culmination height in winter and summer:

"Uh... Yes, I want to rotate it like this but then nothing changes [rotates the Earth while holding the axis on top, like in Fig. 15(a)]. Yes, and I guess it can't rotate like that [flips the axis back and forth, like in Fig. 15(c)]. That would... be strange. Hmm... no... yes. I know the start and end point... Like this."

Still other students switched to a consciously—and sometimes even systematically—moving axis, or did

assume a systematically moving axis from the beginning. They showed the correct extreme positions for summer and winter, but demonstrated a vertical (nontilted) axis for spring and autumn [Fig. 15(b)] or they oscillated back and forth multiple times between these extremes [Fig. 15(c)]. One of these students even questioned whether this motion was purely back and forth or also included a rotational component [Fig. 15(d)]. Although all these students' mental models were incorrect or incomplete, they could theoretically have answered our interview questions correctly, since their model only deviated for spring and autumn—moments not explicitly addressed in our questions. However, similar to the students who correctly demonstrated the orientation of the axis throughout the year, they did not always arrive at a scientifically sound explanation in practice.

Next to the students that moved the axis unconsciously or systematically, other students consciously but unsystematically moved the axis around. One student even rotated the Earth in all possible directions at some point; another held the axis almost horizontally, with the axis appearing to move almost tangentially to Earth's path around the Sun.

Several students—some of those who moved the axis consciously, some who did so unconsciously, and even some who did not really show a tilted axis despite mentioning it—did not incorporate the orientation of Earth's axis as an explanatory factor in their mental model at all. In some students, this awareness emerged only later when answering the generative question about a “straight axis” or the question concerning the cause of the seasons.

Student 4, when asked if something would change if the Earth's axis were not tilted: “Ah, maybe it was something like this, that it rotates like this and then like that. That was maybe what [the drawing] meant. Yes. Something would change, yes. Ah, wasn't this the colder weather? [tilts the Earth's axis away from the Sun] Yes, I think so. That it [the Sun] then lasts longer... But what I'm saying now also doesn't make sense... If it rotates like this for longer, then it's a certain... If it's like this, then it's warmer [tilts the Earth's axis towards the Sun]. Or maybe because it's closer. Yes, that's what I'm assuming now.”

Theme 4: Sunrays and lines of sight.

The role of sunrays and lines of sight. The Sun is a large, distant, light source whose rays can be treated as parallel when they reach Earth, due to the large distance between the Sun and the Earth, as mentioned in paragraph IV B 1. Although the materials we provided were not to scale, students should recognize these characteristics, as the parallel-ray assumption is essential for determining the Sun's apparent position in the sky.

The angle between the incoming sunrays and the horizon plane is known as the angle of incidence. The culmination height of the Sun, i.e., the maximum angle of incidence, varies throughout the year and with the observer's latitude (questions D and B).

At sunrise and sunset, the incoming sunrays lie in the horizon plane. The angle they make with the cardinal direction axis in that plane determines the observed directions of sunrise and sunset, which also vary systematically with latitude and time of year (questions E and C).

Students, however, did not always rely on incoming sunrays when reasoning about the Sun's position. Instead, they sometimes adopted the perspective of an observer and imagined a line of sight extending from the observer's eye toward the Sun. Because the Sun is much larger than the Earth and extremely distant, these lines of sight from observers at different latitudes can be considered parallel, just like the incoming rays themselves.

Recognizing this equivalence between parallel sunrays and parallel lines of sight is important, although students did not need to explicitly mention both to provide a correct explanation. In paragraph IV B 1, we highlighted students' difficulties in defining the cardinal directions. In the following paragraphs, we discuss how incorrect representations of sunrays or lines of sight—even when combined with an otherwise correctly defined coordinate system—can lead to erroneous explanations of the Sun's direction of rise and set.

Student difficulties with the characteristics of sunrays.

Of all students who referred to incoming sunlight at some point in the interview, only five explicitly depicted the sunrays as parallel. Two additional students reasoned as if the rays were parallel but still drew or described them as nonparallel. One student initially represented the rays as parallel but became uncertain and revised their representation as the interview continued. Most students depicted the rays as either diverging or converging. Examples of these different representations are shown in Figs. 16–19. These indicate that most students did not take into account the previously mentioned size of the Sun or the distance between the Sun and the Earth.

Some students used hybrid or inconsistent representations. For example, student 13 initially drew diverging

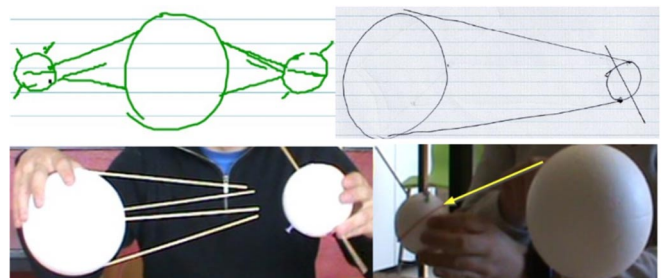


FIG. 16. Examples of sunrays represented or drawn as converging by different students.

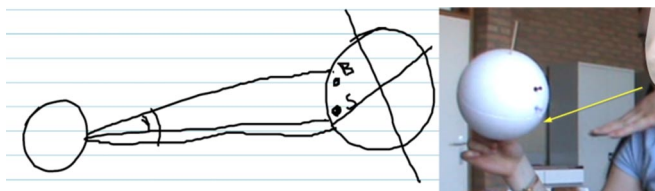


FIG. 17. Example of sunrays represented as diverging by student 18.



FIG. 18. Drawings of the Sun, its rays, and their incidence on Earth at different latitudes, made by student 13. The left drawing was made when answering question D; the right drawing was made after the hypothetical cylinder question.



FIG. 19. Screenshots of student 10 illustrating sunrays using their fingers (left) and wooden sticks (right). At times, they start the sunray at the center of the Sun, while at other moments these rays appear to originate from the upper or lower edge of the Sun.

sunrays but later indicated that they arrive “more or less parallel” on Earth. After responding to the generative cylinder question this student again depicted the rays as diverging from the center of the Sun, while having them arrive approximately parallel on Earth (see Fig. 18). Others, such as student 10, alternated between depicting the rays as diverging, converging, or parallel at different moments in their explanation, as illustrated in Fig. 19.

When explaining the Sun’s culmination height and its variation throughout the year (question B) and with latitude (question D), 12 students initially employed sunrays in their reasoning. Seven of these clearly used angled, nonparallel rays, as illustrated in Figs. 16–19. Five of the students who adopted a sunray-based approach also explicitly referred to perspective or the way one “looks” at the Sun, applying a line-of-sight-based approach.

Using diverging or converging rays or slanted lines of sight automatically leads to latitudinal differences in culmination height, but based on incorrect assumptions. While the Earth’s sphericity may have masked the consequences of this alternative idea in this part of the interview, it became evident in the generative question about a cylindrical Earth.

When considering the questions on the direction of sunrise and sunset (questions C and E), students were generally not inclined to explain differences in terms of incoming sunrays. While seven students did refer to differences in incoming sunlight at some point, they did not make the connection that these sunrays would intersect the cardinal coordinate system in different ways and thus would lead to different directions of sunrise and sunset. Instead, many students relied on their prior beliefs (e.g., that there is no difference at all) or adopted alternative lines of reasoning, such as focusing on the shape of the Sun’s daily arc. This lack of connection is illustrated by the excerpt of student 12: although they described seasonal differences in the angle of incidence, they almost immediately asserted that the Sun rises and sets in the same place throughout the year.

Student 12: “January, December: low angle of incidence. If you stand here [spring], the day is longer. But it still sets and rises at the same place... Yes, you always see it rise and set in the East and the West. It is always in the same place.”

Student difficulties with the characteristics of lines of sight. Nine students mentioned the principle of lines of sight—or the perspective from which one observes—either implicitly or explicitly when answering questions about the Sun’s culmination height. However, in response to the question on seasonal differences in culmination height, it became clear that six students considered their line of sight as angled toward the center of the Sun (so they did not consider the large size of the Sun and the vast distance between Sun and Earth). For instance, student 19, when explaining why the Sun would appear slightly higher in Spain, reasoned from a perspective “from the pins on the Earth” toward the center of the Sun (Fig. 20) and stated:

Student 19: “Because it [Spain] is lower than Brussels, that point. So it will... I mean... I’m not really sure how to say this. But from your perspective, if you just look from there... if I just



FIG. 20. Screenshots of student 19 while reasoning about the seasonal changes in culmination height (question D). The right panel shows that the student consistently directs their gaze toward the center of the Sun.

look from there and I look at the highest one [Belgium], then I simply see that it [the Sun] is that high. But if I go a bit lower [observer in Spain], it seems as if it [the Sun] is higher as seen from my [an observer's] perspective, it [the Sun] seems much higher [in Spain]"

Eight students also employed a form of line-of-sight reasoning when responding to questions about the direction of sunrise and sunset. Again, six of them were affected by the indirect influence of distance and misread the direction of sunrise and sunset. To illustrate, we provide excerpts from student 1 and student 5:

Student 1, in response to the question “How do you infer from the materials that it is more to the southwest?”: “Because it [line of sight] is more slanted [makes a diagonal hand movement toward SW, as shown by left panel of Fig. 21], instead of horizontal [makes a horizontal hand movement toward W, as shown by right panel of Fig. 21] ...But maybe that’s because the Sun is just lying on the ground [table].”

Student 5, when explaining where the Sun sets in May: “Ah wait, that’s more upwards. That’s more towards the north...then [in May] it [the observer] has to look more upward at an angle [points from the pin diagonally upward towards the Sun, as shown in Fig. 22, resulting in the inference—based on their correctly defined coordinate system—that the Sun sets further toward the northwest].”

Student difficulties in connecting differences in orientation with line of sight and/or sunrays. In addition to the difficulties already mentioned, some students recognized that the orientation of a location relative to the Sun changes throughout the year, and that the orientation of Spain relative to the Sun differs from that of Belgium. However, they were unable to relate this to observable changes. They did not connect either lines of sight or sunrays to an observer-based coordinate system. These students often



FIG. 21. Screenshots of student 1 while reasoning about the seasonal changes in sunset directions (question E). They argue that the line of sight is more slanted in winter (left panel), and therefore directed more toward the southwest instead of the west.

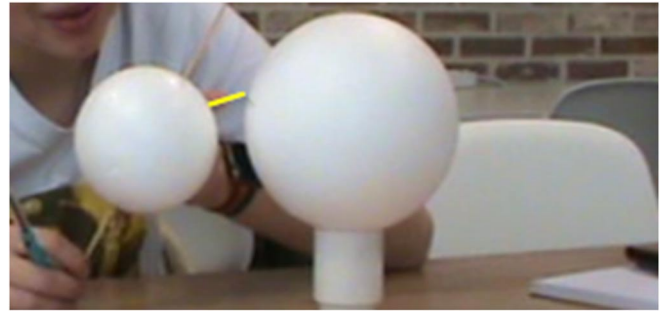


FIG. 22. Screenshot of student 5 demonstrating how an observer in summer views the Sun at sunset. The student indicates a diagonal line of sight toward the center of the Sun (rather than a horizontal line) and infers that in summer the Sun sets further toward the northwest, based on their correctly defined coordinate system.

attempted to explain differences in culmination height by invoking other considerations, such as, for example, known differences in daylength.

Other students were able to represent either sunrays or lines of sight, but failed to grasp that these actually describe the same geometry, merely from different starting points.

Theme 5: The orientation of the Sun’s orbital plane.

The Sun’s orbital plane. The plane in which the Earth revolves around the Sun is referred to as the ecliptic plane. For convenience, it is typically depicted as a horizontal plane. However, this choice of orientation is purely representational: in physical terms, space has no privileged “up” or “down,” and the ecliptic plane may be oriented arbitrarily.

Accordingly, the Earth-Sun system can be described in equivalent ways, as is illustrated in Fig. 23. One may represent the Earth as revolving in a horizontal orbital plane with a rotation axis tilted relative to that plane [Fig. 23(a)], or, alternatively, as having a rotation axis perpendicular to a chosen horizontal reference plane parallel to the equator, while the orbital plane itself is inclined [Fig. 23(b)]. Depicting an inclined orbital plane is therefore not, by itself, incorrect. What is essential, however, is that the Earth’s rotation axis is tilted with respect to the plane of its orbital motion, and consequently that the equatorial plane does not coincide with the orbital plane.

Student explanation of apparent motion based on an inclined orbital plane. In our interviews, representing the Earth as moving in an inclined orbital plane was sometimes triggered by the question addressing seasonal changes in the Sun’s culmination height (question B). In these cases, students depicted the Earth as being higher or “lower” with respect to the Sun, depending on the time of year. They reasoned that when the Earth is positioned higher relative to the Sun, an observer on Earth must look downward, resulting in a lower culmination height at that

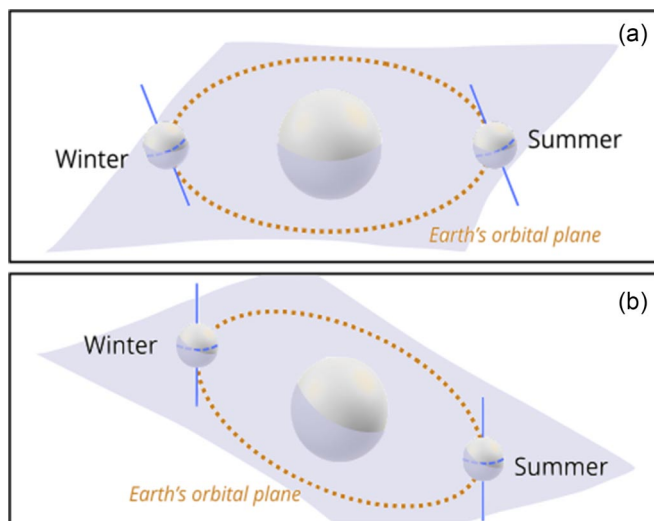


FIG. 23. Two equivalent representations of Earth and its orbit around the Sun. In (a) the conventional depiction is shown, and in (b) an inclined-orbit representation. Note the orientation of the Earth's axes and equators as rendered in each view.

time of year. Conversely, when the Earth is positioned lower relative to the Sun, they inferred that an observer must look upward, leading to a higher culmination height, as is illustrated in Fig. 24.

Two students consistently applied this model throughout the remainder of the interview, whereas two others repeatedly questioned whether the Earth might at times be higher or lower relative to the Sun—including when answering question D—but did not represent this idea consistently in their drawings or explanations.

As a result, the former group represented the plane of revolution as inclined relative to an imagined horizontal

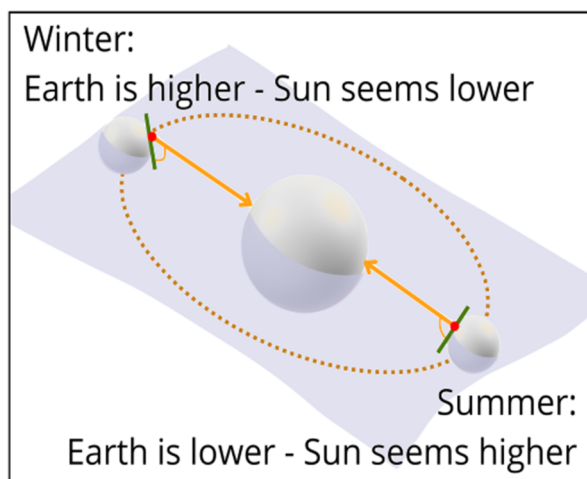


FIG. 24. Schematic illustration of how students use an inclined orbit to explain differences in the Sun's culmination height. The red dot represents an observer, the green line represents a horizon plane (which students did not explicitly mention), the orange arrow represents the observer's line of sight.



FIG. 25. Screenshot of student 19, demonstrating the inclined orbital plane and why you can see the Sun higher in summer and lower in winter.

plane in which the Sun is located. While an inclined orbital plane is not inherently a problem, it became so in these cases because the accompanying conditions were not satisfied: the Earth's rotation axis and/or the equatorial plane were not consistently represented as being tilted with respect to the orbital plane. We illustrate this with a quote and screenshot from student 19 (Fig. 25), as well as a drawing by student 9 (Fig. 26), who reasoned similarly.

Student 19, in response to the question how one can see from the materials that the Sun appears higher in summer:

“Because I think it [the Earth] is lower [in summer], it seems more as if it [the Sun] is in the north, but actually it is just higher. It just looks as if it is closer there. Whereas when it is here [winter], we stand a bit higher—this is exaggerated, but we stand higher—and then it looks as if it [the Sun] is, yeah, more to the south.”

These students also attributed the seasonal variations in the direction of sunrise and sunset (question C) to this difference in height relative to the Sun, because in their view a change in orientation leads to a change in perspective, or in how one sees the Sun. However, they were unable to make this more concrete and to demonstrate it with the materials (at least in part because they did not appear to make a connection to a cardinal coordinate system).

One additional student (S17) began to clearly express the idea of an inclined orbital plane only from the

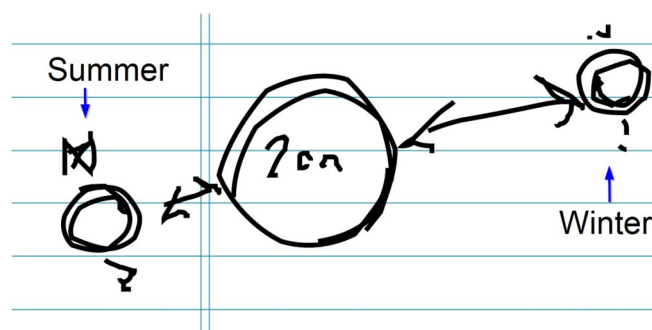


FIG. 26. Drawing of student 9, who depicts the Earth as lower in summer and higher in winter, and also believes the Sun is closer in summer and farther away in winter.

TABLE II. Number of students who expressed alternative ideas (AltId) related to a given theme when explaining a specific aspect of the Sun's apparent motion. Columns correspond to aspects of apparent motion (with R and S = rise and set position, and CH = culmination height); rows represent the overarching themes of difficulty. Each cell reports the number of students. The final column shows the total number of distinct students who expressed alternative ideas related to that theme at any point during the interview. The penultimate row shows the total number of distinct students who expressed at least one alternative idea while explaining a specific aspect. The final row shows the number of students who expressed multiple alternative ideas when explaining a given aspect.

	(A) Daily path with R and S	(B) CH ~ Time of year	(D) CH ~ Latitude	(C) R and S ~ Time of year	(E) R and S ~ Latitude	Theme total (AltId $\geq$ 1)
Cardinal directions	17		2	19	20	21
Role of distance		9	8	4		13
Tilted axis	2	17	9	13	3	18
Inclined plane		3	4	4		4
Sunrays and line of sight		12	17	3	4	19
Aspect total (AltId $\geq$ 1)	18	20	19	21	21	22
Aspect total (multiple)	1	15	13	18	8	20

questions on the seasons onward. As this topic is not part of the present paper, this student is not included in this analysis nor in Table II.

2. Students' understanding of different aspects of apparent motion

Whereas the previous sections described each theme of difficulty in detail and illustrated how these themes manifested in students' reasoning, the present section shifts the focus to students' understanding of the different aspects of apparent motion and to the influence of the various themes on that understanding.

Table II reports, first, the number of students who expressed alternative ideas within a given theme when explaining specific aspects of apparent motion, thereby providing a concise overview of the patterns described in the preceding subsections. Importantly, the presence of a theme in a student's response does not imply that this idea consistently structured the student's final explanation. Rather, it indicates that the idea appeared at some point in the student's expressed mental model. As shown in the table and in the preceding sections, such alternative ideas were very common, although individual students did not necessarily apply the same idea across all related contexts. This becomes clear from the fact that, for each theme, the total number of associated students (final column) exceeds the number reported in any individual cell within that row.

Second, the table provides an overview of how many alternative ideas were expressed while explaining each aspect of apparent motion separately. It is evident that each aspect is associated with multiple themes and that specific themes were more relevant for some aspects than for others. Moreover, many students expressed alternative ideas belonging to several themes when reasoning about one specific aspect. In the following paragraphs, we discuss the main trends visible in Table II for each aspect

of apparent motion. Additional details on the distribution of individual students are provided in Appendix E.

When explaining the Sun's daily path (question A), 18 students expressed at least one alternative idea at some point. Of these, 17 expressed alternative ideas related to the cardinal directions, although four of them eventually defined and demonstrated this system correctly. It is striking that 21 students answered the corresponding AMoSS question correctly (Sec. IVA) and still so many lacked the necessary features and connections in their mental models to explain the underlying mechanism.

A similar trend is seen for the other aspects: 21 and 17 students answered correctly on the AMoSS question on the change in the Sun's culmination height throughout the year (question B) and with observer position (question D). However, when probed to explain these changes, 20 and 19 students, respectively, expressed at least one alternative idea. As in the previous aspect, many students showed combinations of multiple difficulties within a single explanation. The most frequent theme involved difficulties with sunrays and/or lines of sight, likely because these "lines" are essential for representing how an observer determines heights in the sky. In addition, many students expressed alternative ideas related to Earth's axial tilt, particularly when they were asked to slowly demonstrate Earth's revolution using the 3D materials. The influence of distance was also invoked in both aspects. When explaining the seasonal changes of the Sun's culmination height (question B), students often referred to a difference in distance caused by the elliptic shape of Earth's orbit, whereas in explaining the latitude-dependent variations (question D), students attributed differences in distance between two observer positions to the tilt of Earth's axis and/or the spherical shape of the Earth. It is also primarily in explanations of the (variations in) culmination height that several students suddenly depicted Earth's orbit as lying in an inclined plane.

The next aspect studied is the seasonal variation of the position of sunset and sunrise (question C). Again, we saw that students expressed many alternative ideas across all themes. As can be expected, the greatest difficulties arose in defining and using the cardinal directions, and this was also the case for the latitude-dependent variations (question E). Alternative ideas related to Earth's axial tilt appeared frequently as well. Difficulties involving lines of sight and/or sunrays also played a role, although in these questions they were often intertwined with, or even overshadowed by, difficulties related to cardinal directions. Although students generally answered these AMoSS questions less correctly (Sec. IV A), the test results alone (55% correct for question C and 64% correct for question E) would not lead one to expect that nearly all students held alternative characteristics and connections in their mental models at a certain point.

In addition, we note that all students appear at least once in the table, indicating that every student experienced difficulty in explaining at least one aspect of apparent motion. Yet 17 of the 22 students provided four or more correct answers on the five AMoSS questions. As mentioned earlier, many students expressed uncertainty about their answers, but even then, one would not expect that—depending on the aspect—between 18 and 21 students would hold at least one alternative idea in their mental model. This contrast reveals that the picture emerging from the AMoSS results in Sec. IV A was highly flattered: students' ability to select or reproduce the correct description of an aspect of apparent motion did not reflect the nature of the mental models they actually used when explaining these phenomena. The in-depth interviews showed that almost no student possessed a fully developed, scientifically accurate mental model, definitely not for all the aspects of apparent motion together. Ultimately, only a very small number of students were able, after extended reasoning, to construct a scientifically sound explanation for several aspects of the apparent motion of the Sun, and no student was able to do so for all aspects.

V. DISCUSSION

This study used task-based think-aloud interviews with 22 Flemish students (aged 16–18) to probe their understanding of the Sun's apparent motion. Whereas previous studies have often focused on isolated aspects of apparent solar motion—such as whether the Sun can ever appear directly overhead at a given location or how its culmination height varies throughout the year (e.g., [6,7,15,16])—the present study examined students' reasoning across the daily motion of the Sun as well as seasonal and latitude-dependent variations in culmination height and rise and set directions in an integrated manner. By investigating these aspects simultaneously, we found that none of the students in our study were able to explain all aspects of apparent solar motion using a fully scientifically consistent model.

Students who correctly explained certain aspects, such as seasonal changes in culmination height, often experienced substantial difficulties when reasoning about other aspects, for example, seasonal or latitude-dependent variations in sunrise and sunset directions.

In addition, unlike studies that primarily relied on written assessments or multiple-choice instruments (e.g., [3,6,7,9,16,20,25]), our approach explicitly combined three-dimensional materials and generative questions within task-based think-aloud interviews. This methodological combination provided access to aspects of students' reasoning that would remain hidden in more traditional assessment formats.

When considering students' ability to describe the Earth-based phenomena associated with the apparent motion of the Sun, we found that students generally performed well on the AMoSS Sun items, although questions addressing seasonal and latitudinal changes in sunrise and sunset direction proved more difficult (questions C and E; Fig. 1). Many students revised their answers during the interviews, suggesting limited confidence and incomplete underlying models (Table I). Overall, students in our study performed somewhat better than those in Bekaert *et al.* [3], yet did worse on the item concerning seasonal changes in the direction of sunrise and sunset (question C). These differences may result from methodological differences, self-selection, and the small number of participants in our study.

Despite often offering correct descriptions of the observed phenomena, only a minority of students demonstrated a scientifically accurate mental model of the Earth-Sun-observer system to explain these observations. Across interviews and across aspects, alternative ideas repeatedly emerged concerning five overarching themes: cardinal directions, distance, orientation of Earth's axis, sunrays and lines of sight, and the orientation of the Sun's orbital plane.

These findings both confirm and extend previous research on students' understanding of astronomical phenomena. While previous studies have also documented difficulties related to Earth's axial tilt in the context of explaining the seasons (e.g., [7,19]), our findings support those of Plummer and Maynard [24], who reported that students often fail to coordinate their knowledge of Earth's axial tilt with seasonal changes in the Sun's apparent motion. Similarly, although distance-based explanations of seasonal temperature differences are well documented in the literature (e.g., [6,7,14,19]), our findings suggest that these ideas extend beyond reasoning about these temperature differences alone. Many students also relied on distance-related arguments when explaining changes in the Sun's culmination height and seasonal variations in sunrise and sunset directions. At the same time, our study identified several difficulties that, to the best of our knowledge, have received little or no attention in previous literature. These include difficulties defining observer-based

cardinal directions on a spherical Earth, the use of Earth-centered rather than observer-centered coordinate systems, alternative assumptions concerning sunrays and lines of sight, and reasoning based on an inclined orbital plane.

All these alternative ideas substantially influenced students' explanations of the observed phenomena, even in cases where students arrived at a correct answer to the corresponding AMoSS item. All students in our study exhibited difficulties related to at least one of the identified themes, though to varying degrees. Although students did not always express these alternative ideas consistently, they emerged repeatedly in their reasoning, and students frequently combined multiple alternative ideas simultaneously. Also, considerable variation was observed within each theme. Taken together, this variability suggests that categorizing students' expressions into a small number of mental model types, as proposed by Bekaert *et al.* [2,9], may oversimplify the diversity of mental models we observed in the present study. Likewise, judging students' understanding of the phenomena based on whether they select the correct answers may lead to overestimations.

Indeed, our interview data suggest that correct AMoSS responses cannot automatically be interpreted as evidence of conceptual understanding. On the contrary, many students were able to correctly identify or describe aspects of apparent solar motion, and achieved high AMoSS scores, while simultaneously demonstrating incomplete, fragmented, or scientifically inconsistent explanatory models. Moreover, students with similar answer patterns on the test often held very different underlying ideas. Even written explanations, such as those used in Bekaert *et al.* [2,3,9,10], may mask important distinctions, since we found that students who offer similar initial explanations (e.g., invoking axial tilt) often conceptualized the underlying mechanisms in fundamentally different ways.

These observations raise important questions regarding the construct validity of the AMoSS instrument. Boness and Sher [35] argue that assessment items may fail to measure the construct they are intended to assess when respondents can provide seemingly appropriate responses that do not reflect the targeted underlying understanding. Consistent with this argument, our findings suggest that AMoSS may provide a valid measure of students' ability to recognize or describe observable aspects of apparent solar motion, but it appears to be a less valid measure of their underlying conceptual understanding. Gaining deeper insight into students' mental models therefore requires different methods that allow students' reasoning to be explored in greater depth, such as task-based think-aloud interviews.

However, even standard probing during interviews proved not always sufficient to uncover the full structure of students' models. Certain features of a mental model, such as the assumed shape and orientation of sunrays or lines of sight, often remained implicit and could not be inferred with certainty from verbal explanations and

material manipulations alone. In addition, not all students were equally able or willing to externalize their thinking through drawing. In this respect, the generative questions we deployed during the interviews proved particularly valuable. By systematically varying specific features of the model (i.e., the axis tilt, the spherical surface, and the Earth's revolution), we were able to triangulate students' implicit assumptions. For each aspect (e.g., seasonal differences in culmination height), we considered students' responses across both the standard questions and the different generative variations. Examining these responses in combination provided a more coherent picture of their underlying model than any single explanation, drawing, or probe would have yielded. The generative questions therefore represent an important methodological contribution of the present study.

Similarly, the use of three-dimensional materials proved valuable in revealing another recurring challenge: perspective taking. Many students struggled to define and apply a local coordinate system on a spherical Earth model. Some appeared to be unable to mentally situate themselves on the spherical surface and determine cardinal directions from that position. These difficulties hindered their ability to coordinate geocentric and allocentric perspectives and therefore to explain apparent solar motion based on what happens in space. These findings complement work by Plummer *et al.* [5], who showed that perspective taking skills predict children's ability to make explicit allocentric connections when explaining stellar motion. However, they did not observe such a relationship for explanations of the Sun's apparent motion, possibly because learners are more familiar with the Sun's apparent motion and therefore rely on familiar, egocentric heuristics (e.g., "it is higher in summer"), which bypass the need to coordinate reference frames. In our study, when explicitly asked to use an allocentric model to explain the Sun's motion, many students experienced difficulties and reverted to isolated facts (e.g., about the poles or daylength) rather than coordinating the relevant spatial characteristics.

Another recurring difficulty involved causal reasoning. Many students struggled to distinguish causes from consequences within the Sun-Earth system. For example, several used the change in daylength as an explanation for differences in culmination height and/or sunrise and sunset directions, although these phenomena all derive from the same underlying cause: Earth's axial tilt and its changing orientation relative to the Sun. However, this underlying mechanism remained unclear for many students.

More generally, students did not appear to hold fully articulated, preexisting ideas about the mechanisms underlying the Sun's apparent motion. Instead, they seemed to construct parts of their models "on the spot." This observation aligns with the assumptions of Vosniadou and Brewer [1,11] regarding the dynamic nature of mental models. When prompted to explain their observations based on what happens in space, students were compelled

to construct a more sophisticated mental model, often filling conceptual gaps by generating new, sometimes incomplete or incorrect, assumptions. Difficulties with Earth's axial tilt illustrate this: some students held preexisting alternative ideas (e.g., a wobbling axis), while others introduced such ideas during manipulation of the materials, or while trying to interpolate between winter and summer positions. Similar effects were reported by Atwood and Atwood [19], who noted that physical materials can shape participants' explanations and thus mental models. The precise dynamics of this modeling process are not yet fully understood and may constitute an interesting topic for future research.

VI. LIMITATIONS

Given the highly intensive data collection and coding, this study relies on a relatively small sample. The value of the work therefore lies less in the quantitative patterns (although Table II clearly gives an indication of how many students can provide a fully correct explanation) but more in the depth of insight it offers into students' alternative ideas. At the same time, both the interview approach and our interpretation of the data introduce potential limitations.

A first limitation concerns the recruitment procedure. Participation in the study was voluntary, which may have introduced a degree of self-selection bias. Students who chose to participate may have been more motivated, more interested in science, or more willing to engage in extended discussions about scientific phenomena than the broader student population. In addition, the majority of participants were enrolled in science-oriented study programs. Consequently, the sample cannot be considered representative of all Flemish secondary school students, and the findings should not be generalized without caution. At the same time, it is important to note that even these relatively motivated students often experienced substantial difficulties in describing and explaining the apparent motion of the Sun. Given that many participants were enrolled in science-oriented study programs and had successfully completed formal instruction on the topic, the challenges identified in this study are unlikely to be restricted to this particular group of students and may be even more pronounced in a broader student population. Nevertheless, further research with more diverse and systematically sampled populations is needed to investigate the extent to which the observed reasoning patterns generalize beyond the present sample.

A second limitation concerns the inferences we draw about the content and structure of students' mental models. Because these models are internal constructs and therefore not directly observable [11], we must rely on our interpretations of students' verbal statements, drawings, and use of the 3D materials [30,36]. These externalizations offer only indirect access to students' thinking.

The materials and drawings helped many students articulate their thinking. This was particularly important because many students lacked the vocabulary to express their understanding: they often used scientific terms without attaching precise meaning to them. For example, several students struggled to define or correctly use the "*angle of incidence*" or misinterpreted the concept of "*ecliptic plane*." Such examples illustrate the interpretive challenges of relying on students' verbal statements alone and highlight the value of triangulating with multiple elicitation formats. They also underscore the importance of language (development) in science learning.

Another limitation concerns the materials themselves. While the 3D representations supported many students in reasoning more deeply and sometimes prompted them to refine their explanations, their use may have functioned as a form of intervention, even though our aim was solely to probe students' existing mental models rather than to influence them. At the same time, the models introduced potential distortions: they necessarily contained scale inaccuracies (e.g., relative sizes and distances). As a result, some students drew incorrect conclusions or were misled by representational features. These factors should be considered when interpreting the mental models expressed in this study.

A further limitation concerns the interpretation of students' responses to the generative questions. These questions were partially designed to elicit students' implicit assumptions without introducing interviewer-induced cues. However, interpreting these responses as direct evidence of students' underlying mental models implicitly assumes that their reasoning remains stable across tasks. Our data suggest that this assumption does not always hold. In the cylindrical Earth questions, for instance, several students did not explicitly mention distance, yet their explanations for the inclined axis cylinder revealed direct or indirect distance-related considerations—sometimes seemingly without conscious awareness. This pattern indicates that students may initially apply different assumptions to the vertical axis and inclined axis versions of the task. Consequently, interpretations of the generative-question responses require caution, and the reasoning processes underlying these responses require further investigation.

VII. CONCLUSION

Our analysis indicates that correct responses to the AMoSS questionnaire cannot automatically be interpreted as evidence of conceptual understanding of the apparent motion of the Sun. From a construct validity perspective, our findings raise questions about the extent to which the instrument measures the underlying conceptual understanding it is intended to assess. Task-based think-aloud interviews provide richer and more reliable insights into the underlying mental models.

Students expressed a range of alternative ideas clustered around five themes: cardinal directions, distance, axial orientation, lines of sight and sunrays, and the orientation of the Sun's orbital plane. Evidence suggests that students construct more sophisticated models only when the task environment explicitly elicits such reasoning. Future work should examine the dynamics of this modeling process in more detail.

Relying exclusively on students' verbal explanations risks misinterpretation: students may lack the scientific vocabulary needed to express their ideas accurately, or they may use scientific terms with noncanonical meanings. Physical materials can therefore play an important role, as they support both the construction and the externalization of mental models. However, physical models also inevitably distort the true scale of astronomical systems and can lead students to incorrect inferences. Moreover, because many students experience difficulties with perspective taking, the mere presence of physical models does not guarantee that students can explain astronomical observations in an allocentric manner.

Together, these findings highlight the importance of combining multiple forms of "evidence" when assessing students' understanding of astronomical phenomena and suggest promising directions for future research into students' reasoning and model construction.

ACKNOWLEDGMENTS

The authors would like to thank the participating schools and the students for their openness and collaboration in the interviews, which made this study possible. This research is funded by the Research Foundation Flanders (FWO) under Contract Number G037824N.

DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

APPENDIX A: BASIC INTERVIEW QUESTIONS

In this section, we provide the basic interview questions that were derived from the AMoSS test. Each question corresponds to a specific aspect of the Sun's apparent motion. Question B/C is designed to prompt a recapitulation of students' earlier explanations concerning seasonal variations in both culmination height and rise and set position. Question D/E is intended to elicit a recapitulation of students' explanations concerning latitudinal variations in culmination height and rise and set position.

Question A: Suppose we are in Brussels, on April 15th. At that moment we see the Sun high above the southern horizon, as shown in the figure. Can you indicate on this figure (Fig. 27) where we would see the Sun one hour later?

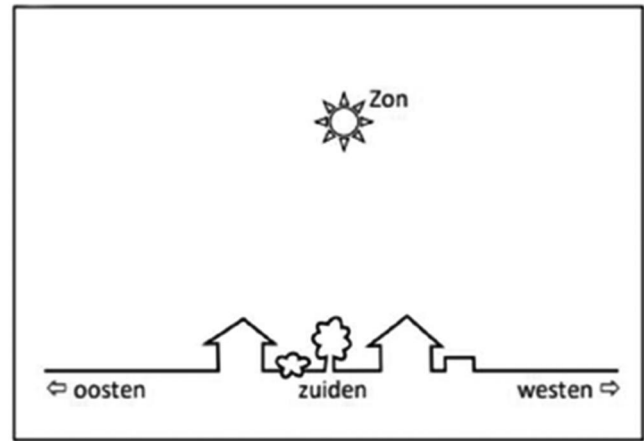


FIG. 27. Question A.

Question B: On January 10th, in Brussels, we see the Sun at its highest point as shown in the figure (Fig. 28). Where do we see the Sun at its highest point on June 10th, compared with January 10th?

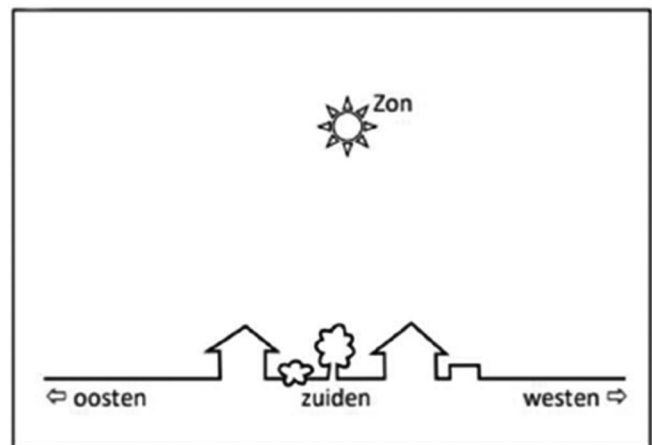


FIG. 28. Question B.

Question C: We are again in Brussels. In September, we see the Sun setting in the west, as shown in the figure. Where do we see the Sun set a few months later, in December? Please indicate it on the figure (Fig. 29).

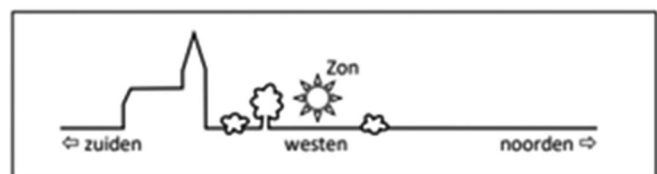


FIG. 29. Question C.

Question B/C: Earlier, you already drew the Sun's path on April 15th (question A). Could you now draw the

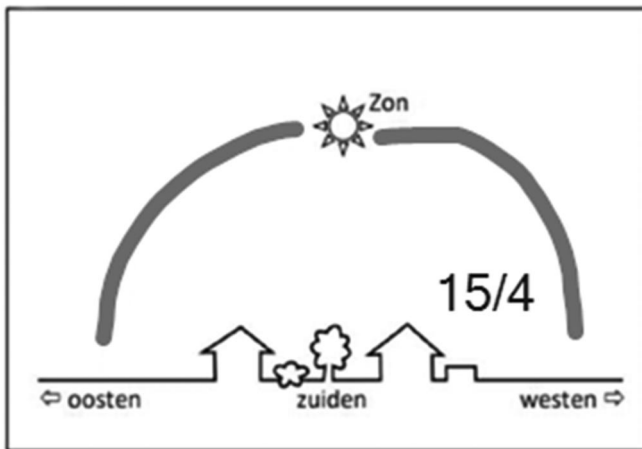


FIG. 30. Question B/C. The path labeled “15/4” represents the path that the student had drawn when answering question A.

complete path of the Sun on June 15th? Please use a different color on the same figure (Fig. 30).

Question D: Suppose it is winter, and we are still in Brussels, observing the Sun at its highest point. Where would an observer in the south of Spain see the Sun at its highest point on the same day? Indicate it on the figure (Fig. 31).

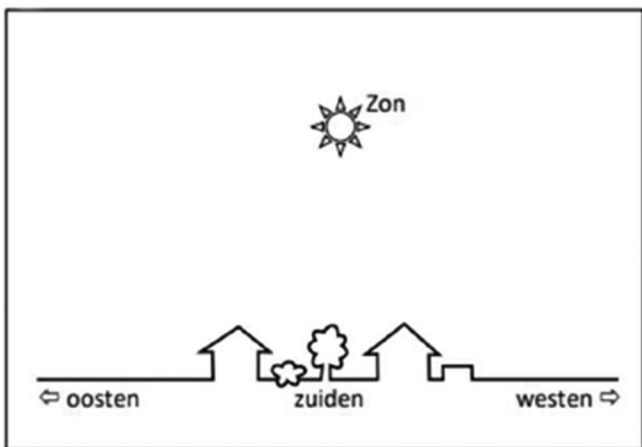


FIG. 31. Question D.

Question E: Do you think the direction in which the Sun sets will be the same or different for the two observers, when one person is in Belgium and the other in Spain? (In which direction would it shift: more toward the north, east, south, or west?)

Question D/E: Suppose you are in Leuven, and in winter you see the Sun move across the sky as shown in this figure. The dashed line that is drawn represents the Sun's daily arc. How would an observer see the Sun's daily arc on the same day, but in the south of Spain? Please indicate it on the figure (Fig. 32).

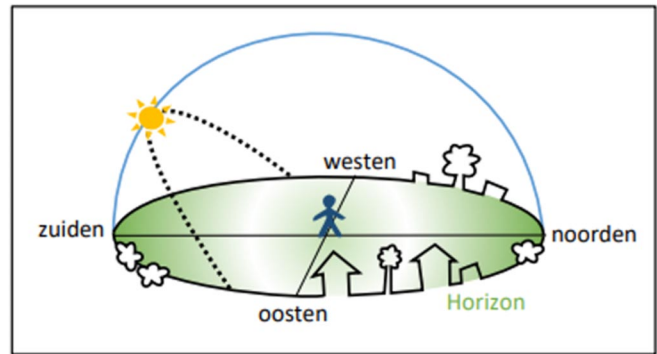


FIG. 32. Question D/E.

APPENDIX B: INTERVIEW PROTOCOL CONCERNING ASPECT B: SEASONAL CHANGES IN CULMINATION HEIGHT—TRANSLATED IN ENGLISH

Starting question B: On January 10th, in Brussels, we see the Sun at its highest point as shown in the figure. Where do we see the Sun at its highest point on June 10th, compared with January 10th? (student indicates on the figure)

Probing questions:

- Why do you choose this location?
 - Explain.
 - Why can't it be ...or ...? (Interviewer fills in based on student answer)
- How could you explain why the Sun appears higher/lower/the same (depending on the student's answer) in June than in January?
 - Why exactly is that? How does that work? What mechanism is behind this?
 - Try to show with the materials, or by drawing, how you think this works. (Probe the why, stimulate student to draw/manipulate)
- And what if we now look at the Sun's highest position in May—would it be in the same place as in June? Do you think the difference between May and June is as large as the difference between January and May?
 - Why/why not?
- And if we continue further into the year—for example, around August 20th—what do we see then? Where is the Sun's highest position at that time (relative to June 10th)?
 - How is that possible?
 - What mechanism underlies this?
- How does this continue throughout the year? Does this pattern keep going? Is there also a moment when the Sun is lower than on January 10th? (probe if student knows about the turning points in June and December)
 - When would that be?
 - Why does that occur?

- Can you use the objects to show how you imagine this? What happens, and how does that correspond to what we observe? (Let student make assumptions explicit: You said/drew ...Does this correspond to what we see with the materials? How come you conclude the Sun is higher/lower?)

Starting question B/C: Earlier, you already drew the Sun's path on April 15th (question A). Could you now draw the complete path of the Sun on June 15th? Please use a different color on the same figure.

Probing questions:

- I see that you draw the path higher/lower and also wider/narrower/the same width (depending on the student's answer). What does that mean for what we would observe on June 15th (compared with April 15th)?
 - What about the Sun's highest point? Does anything change there?
 - What about sunrise and sunset? Does anything change there?
- Does this match what you showed/expained to me earlier?
 - Why or why not?

**APPENDIX C: INTERVIEW PROTOCOL—
GENERATIVE QUESTIONS**

Generative questions G1 and G2 probe properties of the Sun's daily arc—ideas that students may have encountered in instruction, yet still require them to reason with their underlying mental model. Questions G3 through G6 are purely hypothetical: students must modify a specific aspect of the model and explain how this change would affect the observations made on Earth. These final four generative questions follow the same question structure.

G1: Why do we see the Sun's path as part of a circle? Why do we see an arch and not a circular path in the sky?

- Could we ever see a full circular motion here in Belgium? Why or why not?
- If we did observe a full circular path, what would that imply?

Under what conditions would a full circular motion become visible? What would have to change?

Are there places on Earth where a full circular path can be observed?

- Is it always like that at that location?

- Why? How can this be explained?

Can you show your reasoning using the materials or by drawing?

G2: Does the Sun ever stand directly overhead, here in Belgium?

- Why or why not?
- What mechanism causes this?
- What would have to change for the Sun to stand directly overhead?
- Are there places on Earth where the Sun can stand directly overhead?
- Is it always like that at that location?
- Can you show this using the materials?

G3: What if Earth's axis were not tilted?

G4: What if the Earth were not spherical but cylindrical, and had a vertical, non-tilted axis?

G5: What if the Earth were not spherical but cylindrical, and had a tilted axis?

G6: What if the Earth did not orbit the Sun, but only rotated on its axis?

Probing questions considering G3-G6:

- Would we still see the Sun move? Why?
- Would we still have day and night? Would the daily arc look the same as it does now?
 - What about daylength?
 - What about sunrise and sunset?
- Would the Sun appear at a different height in the sky throughout the year? Why?
- Would the positions of sunrise and sunset change through the year? Why?
- Would we see the Sun at the same height if we were in southern Spain? Why?
- Would sunrise and sunset occur in the same direction, in Spain and in Belgium? Why?
- Would there still be seasons? Why?
 - Would effects differ depending on your latitude?
- Can you show with the materials or with a drawing how you imagine this?

**APPENDIX D: CODING SCHEME
FOR QUESTION B**

Figure 33 shows the coding scheme used to analyze the responses related to aspect B, the seasonal changes in culmination height.

Phenomenon of interest: AMoS	✓	Elements needed in explanation	Spatial, structural, moving characteristics of elements	✓	Connections (between elements and characteristics)	✓	Explanation * = essential characteristics of	✓
Seasonal changes in Cumnation Height B		Earth	has a axis		E-O-S have an orientation towards each other (A)		Because the Earth rotates on its tilted axis , but also revolves around the Sun > relative position of a particular place on Earth to the Sun changes throughout the year > sunrays strike the horizonplane in a different angle > different (culmination) height is perceived OR >you look at the Sun in a different angle throughout the year	
			tilted (<i>relative to ecliptic plane</i>)		orientation E(O)-S depends on movement of Earth (2)			
			stable: moves parallel to itself					
			rotates on its axis					
			counterclockwise					
			revolves around the sun					
			counterclockwise		showing 3D movement correctly			
			1 revolution = 1 year		half of a revolution is 6 months, 1/4 is 3 months			
		Sun	fixed (2)					
			far away					
			shines/light/sunrays		strike the Earth/horizon plane			
		Observer			make angle with Earth/horizonplane (5)			
					angle depends on orientation E-(O)-S (A)			
			defines a horizonplane (on Earth) (3)		looks at the Sun			
					in a certain angle (5)			
					angle depends on orientation E-(O)-S (A)			
		altitude	(5) vertical angle between horizonplane/Earth and Sun/sunray > perceived (culmination) height					
Mark as: Always correctly stated (+) Always incorrectly stated (-) Not mentioned (/) Unclear what is meant/if connection is there (?) Changing ideas (+/- or -/+) > specify turning point							Correct (+) Incorrect (-) Incomplete (~) Absent (0) Specify alternative ideas	

FIG. 33. Coding scheme for question B, as described in Sec. III C.

APPENDIX E: DISTRIBUTION OF ALTERNATIVE IDEAS AT THE LEVEL OF INDIVIDUAL STUDENTS

Table III complements the aggregated counts reported in Table II by showing the full individual level distribution of alternative ideas across aspects. The annotations indicate how these ideas evolved during the interview: bold numbers mark cases in which students later revised their reasoning; numbers between brackets (...) indicate revisions within the same question; a question mark (?) denotes uncertainty in the researchers' coding; and italic numbers identify ideas that were first explicitly mentioned during the generative questions. The totals in the final column and the last two rows correspond to the theme level and aspect level counts reported in Table II, but here the individual students contributing to each total are explicitly listed.

TABLE III. Distribution of alternative ideas at the level of individual students.

	(A) Daily path with R and S	(B) CH ~ Time of year	(D) CH ~ Latitude	(C) R and S ~ Time of year	(E) R and S ~ Latitude	Theme total (AltId ≥ 1)
Cardinal directions	(1), 3, 4, (6), 7 8, 10, 11, 12, 14 (15), 16, 17, 18 19, 21, 22		9, 10	1, 2?, 3, 4, 6 7, 8, 9, 10, 11 12, 14, 15, 16 17, 18, 19, 20 21, (22)	1, 2?, 3, 4, 5 6?, 7, 8, 9 10, 11, 12, 14 15, 16, 17, 18 19, 20, 21, 22	21
Role of distance		2, 4, 7, 9, 11 14 , (15), 17, 21	(1), (3), 4, (6), (7) (9), (15), 17, 18	2, (9), 11 , 21	15	13
Tilted axis		(1), 2, 3, 4, 5 6, 7, 8, 9, (10) 11 , 14, 15, 17 18, 19, 20, (21)	2, 4?, 7?, 9, 14 17, (18), 19, 21	2, 3, 5, 6?, 7 9, 14, 15, 17 19, 20, 21	2, 20, 21?	18
Inclined plane		(1), 9, 19	(1), (3), 9, 19	(1), (3), 9, 19		4
Sunrays and line of sight		(1?), (2?), 3, 4 6, 7, 8?, 9, 10 12 , 14?, 17, 18? 19?, 21, 22	1, 2?, 3, 4, 5 6, 7, 9, 10, 12 13 , 14?, 17, 18 19, 20 , 21, 22	1, 2?, 4, 5? 10, 12?, 20 22?	4?, 9?, 10 12, 21	19
Aspect total (AltId ≥ 1)	18	20	19	21	21	22
Aspect total (multiple)	1	15	13	18	8	20

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