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Elementary preservice teachers' application of spatial visualization to explain astronomical phenomena

Jennifer Wilhelm [1*], Rebecca McNall Krall [1], Caroline Murphy [2], Bryan Birch [3], Javier Cantu [3], Pryanna Alper [3]

[1] Department of Teaching and Learning, University of Kentucky, Lexington, KY, USA

[2] Department of Curriculum & Instruction, University of Kentucky, Lexington, KY, USA

[3] Division of Science and Mathematics, Centre College, Danville, KY, USA

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Abstract

This sequential explanatory mixed-methods study examined in what ways preservice teachers (PSTs) visualized astronomical concepts they are expected to teach. We utilized a spatial visualization theoretical framework to investigate: (a) What do PSTs' survey responses on a lunar phases and seasons assessment reveal about their spatial awareness regarding astronomical phenomena? (b) During qualitative interviews, in what ways do PSTs apply their spatial thinking towards explaining astronomical phenomena? Quantitative data consisted of a content survey assessing cause of phases, cause of seasons, and visualization of Earth/Moon/Sun scale. Qualitative data involved interviews concerning 2-dimensional/3-dimensional Earth/Moon/Sun modelling of lunar phases and Earth/Sun modelling of seasons. In comparing Earth-based and Space-based spatial perspectives, PSTs performed better on Earth-based questions concerning cause of seasons. Our findings support the need for developing PSTs' ability to mentally rotate, transform, and coordinate celestial bodies in both Earth-based and Space-based frames in order to understand astronomical phenomena.

Keywords: preservice teacher education, geometry and spatial reasoning, astronomy education

INTRODUCTION

This study examined how elementary preservice teachers (PSTs) visualize and conceptualize astronomical phenomena they are expected to teach. Sixty PSTs from an elementary methods class were assessed on their understanding of causes of lunar phases and seasons as well as understanding the scale (SC) of the Earth/Moon/Sun system. This research investigated how elementary PSTs navigated Earth/Moon/Sun geometric configurations, motions, and SC to explain lunar phases. Specific spatial domains measured were periodic patterns (PP), geometric spatial visualization (GSV) (a Space-based perspective), cardinal directions (CDs) (an Earth-based perspective), and spatial projection (SP) (an Earth-based perspective). Similarly, we explored how elementary PSTs traversed Earth/Sun motions and configurations including Earth's tilt to explain cause of seasons. Spatial domains measured were Earth's axis tilt, Earth's revolution around the Sun (Space-based perspectives), and varied sunlight (Earth-based perspective).

Literature Review

Understanding the causes of lunar phases and seasons commonly appear in K-12 science education standards around the world. These concepts are introduced in the elementary grades and reappear in middle and secondary grades to introduce spatial and geometric thinking to explain causes of astronomical phenomena (e.g., Department of Education, 2014; Finnish National Agency for Education, 2016; Kultusministerkonferenz, 2020; Ministério da Educação, 2018; Ministry of National Education, 2018; Ministry of Education of the People's Republic of China, 2022; NGSS Lead States, 2013).

✉ jennifer.wilhelm@uky.edu **(*Correspondence)** ✉ rebecca.krall@uky.edu ✉ caroline.murphy@uky.edu
✉ bryan.birch@centre.edu ✉ javier.cantu@centre.edu ✉ pryanna.alper@centre.edu

Contribution to the literature

- PSTs have historically struggled with the astronomical concepts of cause of lunar phases and cause of seasons. We contend that such struggles originate with their limited ability to visualize the Moon, Sun, and sky from both an Earth-based and Space-based perspective.
- In our study, we utilized a spatial visualization framework to analyze how PSTs' astronomical conceptions relate to Earth-based and Space-based perspectives.
- Our findings showed that PSTs performed better on Earth-based perspective questions that dealt with cause of seasons content. However, qualitative interviews revealed PSTs struggled the most with spatial visualization areas concerning mental rotation and geometric coordination of the Earth/Sun/Moon for lunar phases understanding and Earth/Sun for season understanding.

Observing celestial phenomena, such as day and night, periodic changes in the shape of the Moon, and changes in the Sun's apparent trajectory and location as it rises on the eastern horizon, traverses the sky, and sets on the western horizon are easily observable phenomena we experience every day. However, making sense of these phenomena has proven to be difficult for children and adults alike without carefully planned instructional intervention (Atwood & Atwood, 1995, 1996, 1997; Bell & Trundle, 2008; Wilhelm et al., 2018; Uçar, 2014). Much like the effect we experience observing the environment flying by as we seem to sit stationary on the merry-go-round platform, our seemingly stationary Earthly vantage point creates the illusion that the sky is moving and we are stationary.

Making sense of the cause of Moon phases and seasons requires the ability to switch between our Earth-based perspective and a Space-based perspective (Plummer et al., 2016). The Earth-based perspective offers a view of the apparent motion we see of the celestial sky. Whereas the Space-based perspective catapults the observer into space where the geometric orientations and movement of the Sun, Earth and Moon can be observed. From the Earth-based perspective, the movement of the Sun and Moon across the sky and changing location and phases of the Moon can be easily observed. The Space-based perspective affords the ability to observe revolutions and rotations of the Earth/Moon/Sun system to make sense of Moon phases, and the Earth/Sun system to make sense of seasons. Switching back and forth from the Earth-based and Space-based perspective using physical and technology models (e.g., simulations) can develop a more scientific view (Plummer et al., 2016; Trundle et al., 2002, 2010; Wilhelm et al., 2018). However, research has found that developing a scientific understanding of the causes of Moon phases and seasons requires repeated experiences with models (Atwood & Atwood, 1997; Cole et al., 2022; Plummer et al., 2016; Wilhelm et al., 2018) and technology (Bell & Trundle, 2008). Even so, it is common for students to continue to struggle with a full understanding (Plummer et al., 2016).

Spatial Visualization Theoretical Framework

In terms of astronomy, spatial visualization of celestial bodies (i.e., the Moon, planets, and stars) and their heavenly motions are more complex than most people realize; it is inherently abstract. The necessary spatial skills vary by astronomy topic, but spatial ability contributes to understanding astronomical topics such as cause of lunar phases and cause of seasons. Learners are introduced to such ideas in the form of 3-dimensional (3D) physical models as well as 2-dimensional (2D) representations with the idea that these ways of understanding will translate to mental visuo-spatial abilities where they mentally manipulate the SC, orbit, and geometric orientation of the celestial bodies at play (Makamure & Jojo, 2021; Miragliotta & Baccaglini-Frank, 2018). Previous research has documented persistent conceptual challenges students face when constructing scientific explanations from 2D and 3D models. For example, Trundle et al. (2007) found that PSTs often struggled to create accurate 2D representations that explained the observed phases of the Moon. Furthermore, although some PSTs were able to correctly model lunar phases using 3D representations, they were unable to construct coherent verbal explanations that accounted for the motions depicted by those models. Similarly, Eriksson et al. (2014) reported that students frequently interpreted 3D models and simulations from a 2D perspective, overlooking critical spatial features such as depth, relative position, and SC, all of which are essential for understanding dynamic astronomical phenomena.

In addition, Plummer et al. (2014) found that learners must coordinate both Earth-based and Space-based perspectives to develop scientific explanations of astronomical phenomena. However, the cognitive demands associated with integrating these perspectives were often too great for students to successfully construct complete scientific explanations. At the same time, relying on a single representation was insufficient for developing a robust understanding of the underlying phenomena. Successfully linking 2D and 3D models with observational evidence requires complex mental-modeling processes that many learners find difficult.

Collectively, these findings suggest that constructing scientific explanations of astronomical phenomena requires instructional scaffolds that support students in interpreting multiple representations, connecting them to observations, and coordinating ideas across 2D and 3D models.

The United States next generation science standards (NGSS Lead States, 2013) and common core state standards – mathematics (National Governors Association, 2010) discuss the importance of student understandings related to spatial-scientific learning (i.e., SC, patterns, and modelling). Research literature has connected increased spatial reasoning ability, including Earth-based and Space-based visualizations, with an increased understanding of concepts such as lunar phases and seasons (Cole et al., 2015, 2018; Plummer, 2014; Plummer et al., 2014).

Predominant misconceptions that students hold to explain cause of the Moon's phases includes Earth's shadow, Sun's shadow, and object blocking notions (Wilhelm et al., 2018). In addition to this, students often are not aware that the Moon orbits the Earth and if they do, they do not know the time period of one lunar orbit (Trundle et al., 2002). Similarly, students lack understanding about the cause of seasons often holding the following misconceptions

(1) incorrect distance between Sun and Earth (thinking Earth is closer to the Sun in the summer),
(2) thinking the direction of the Earth's axis during orbit around the Sun changes throughout the orbit,
(3) incorrect time duration of one Earth rotation on its axis, and
(4) visualizing that the Sun revolves around the Earth (Ashcraft, 2006; Atwood & Atwood, 1996; Bakas & Mikropoulos, 2003; Bisard et al., 1994; Kikas, 2004; Trumper, 2001a, 2001b, 2001c, 2006; Wild & Trundle, 2010).

As noted previously, elementary PSTs often struggle to explain key astronomical phenomena they are expected to teach, particularly the causes of lunar phases and seasons (e.g., Plummer et al., 2016; Wilhelm et al., 2018, 2022). We argue that these difficulties stem, in part, from limited ability to visualize the Earth/Moon/Sun system and Earth/Sun system from both Earth-based and Space-based perspectives as well as limited ability to apply 2D and 3D spatial reasoning when constructing scientific explanations. These are areas that are not well represented in the research literature. Guided by this premise, the present study examined elementary PSTs' understanding of lunar phases and seasons from Earth-based and Space-based perspectives. In addition, we investigated how a subset of participants employed spatial thinking while explaining these phenomena during concept interviews.

Research Questions and Participants

We examined PSTs' spatial awareness of astronomical phenomena from both Earth-based and Space-based perspectives. Research questions included:

(a) What do PSTs' survey responses on a lunar phases and seasons assessment reveal about their spatial awareness regarding astronomical phenomena?
(b) During qualitative interviews, in what ways do PSTs apply their spatial thinking towards explaining astronomical phenomena?

The first question took a quantitative lens to identify what Earth-based and Space-based perspectives PSTs demonstrated in the multiple-choice survey (described later in this section). The second question adopted a qualitative lens to explore how a subset of elementary PSTs applied Earth-based and Space-based perspectives to explain causes of lunar phases and seasons in concept interviews.

These questions were explored with 60 undergraduate PSTs from one south-central university in the United States. The participants in this study were PSTs enrolled in an elementary science methods and a mathematics methods course taken during their senior year. The participants completed two courses in mathematics and one course in physics designed for elementary and middle school PSTs during either their sophomore or junior year. Although the science and mathematics methods courses did not address lunar phases or seasons, the pre-requisite physics course was constructed to align with the national science education standards (National Research Council, 1996; NGSS Lead States, 2013) and included coursework and hands-on activities addressing the causes of lunar phases and seasons. Of the 60, 57 PSTs were female (1 Hispanic American, 1 Asian American, 4 African American, and 51 White) and 3 were male (1 Native American, 2 decline to answer).

Research Methods

For this sequential explanatory mixed methods study, data collection involved administering the astronomical assessment survey, a combined inventory of the lunar phases concept inventory (LPCI) (Lindell & Olsen, 2002), Earth/Moon/Sun scaling questions, and a seasons concept inventory (SCI) (Krall et al., 2023) followed by semi-structured interviews with five PST volunteers.

The research questions guided the data collection creating a sequential process that occurred in two phases to address first the quantitative survey data followed by the qualitative interview responses. In phase 1, PSTs volunteered to take the astronomy assessment survey in their elementary science methods course, taking students approximately 29 minutes to complete. Phase 2 was conducted within two weeks of taking the survey

Table 1. Lunar phases concept inventory spatially coded

LPCI scientific domains			Spatial domains
A – Period of Moon's orbit around Earth	B – Period of Moon's cycle of phases		**Periodic patterns – PP** (*regular intervals of time and/or space; Earth- and Space-based perspectives*)
C – Direction of the Moon's orbit around Earth	E – Phase due to Sun/Earth/Moon positions	G – Cause of lunar phases	**Geometric spatial visualization – GSV** (*visualizing the geometric spatial features of a given system as it appears in space; Space-based perspective*)
D – Moon motion from Earthly perspective	F – Phase-location in sky-time of observation		**Cardinal directions – CD** (*object's vector direction in space as a function of time from a given position; Earth-based perspective*)
H – Effect of lunar phase with change in Earthly location			**Spatial projection – SP** (*projecting oneself into a different location, confined to the surface of Earth, and visualizing from that global perspective; Earth-based perspective*)

where five students volunteered to be interviewed regarding their understanding of causes of lunar phases and seasons.

The 38-item astronomy assessment survey was composed of three parts: LPCI, scaling questions, and SCI. The LPCI is a 20-item multiple choice instrument that assesses eight science domains and 4 spatial domains (see **Table 1** for definitions). Four scaling questions were added to the lunar phases portion of the astronomical assessment survey to gauge PSTs' conceptions of the relative size and distance between the Earth, Moon, and Sun. The SCI was constructed using 14 questions from previously published concept inventories (Bakas & Mikropoulos, 2003; Roald & Mikalsen, 2001; Sadler et al., 2009; Trumper, 2006; Wild & Trundle, 2010). Questions were selected to address four domains presented in Wild and Trundle (2010). The domains included:

(1) Earth's axis is tilted,

(2) Earth orbits Sun,

(3) Variable sunlight, and

(4) day and night are caused by Earth's rotation on its axis.

The lunar phases questions were coded as Earth-based or Space-based. In addition, each question was spatially coded as PP, GSV, CD, SP, or SC, see **Table 1**. The seasons questions were also coded as Earth-based or Space-based. In addition, each seasons question was coded as one of five domains: axis tilt, Earth orbits Sun; variable sunlight, cumulative (a combination of domain 1-domain 3), and rotates on axis.

These interviews were semi-structured and designed to probe deeply into the PST volunteers' thinking. Protocol questions included requests to illustrate both 2D and 3D explanations for why we see lunar phases and what causes seasons. The average interview time was approximately 25 minutes. A constant comparative method (Corbin & Strauss, 2008) was used to analyze interview transcripts to identify the perspective and spatial reasoning PSTs applied in their explanations of lunar phases and seasons. Specifically, PSTs' interview responses were coded as an Earth-based or Space-based perspective in conjunction with their ability to mentally rotate, transform, and configure specific orientation and motions of celestial bodies. Along with the spatial visualization framework, we also focused on asset spatial thinking utilizing diSessa's (2018) "knowledge in pieces" (KiP) framework. According to diSessa (2018):

> Complex systems are built from "smaller" elements, and indeed, system change is likely best understood at the level of transformation and re-organization of system constituents. So, for example, the battery of "little" ideas, intuitions, which constitute "prior conceptions," can be selected from, refined, and integrated in order to produce … normative concepts. Since normative concepts are viewed as systems, their properties as such—both pieces and wholes—are empirically tracked. I describe a focus on both elements and system-level properties as structurally multi-scaled…This theme is not so much a built-in assumption of KiP, but it is one of the most powerful and consistent empirical results. Naïve knowledge is, in general, rich and escapes simple characterizations (e.g., as isolated "misconceptions" and simple false beliefs). Furthermore, learning very often—or always—involves recruiting many "old" elements into new configurations to produce normative understanding. (p. 68)

In our work, we paid attention to PSTs' spatial knowledge where they displayed their asset spatial awareness/thinking/reasoning along with naïve knowledge to build their explanations towards explaining the astronomical phenomena of Moon phases and seasons. We define spatial awareness, thinking, and reasoning as a three-tiered framework.

1. **Spatial awareness —** The learner recognizes that spatial properties (position, orientation, distance, arrangement) and the presence of moving versus stationary elements could affect what is observed.
2. **Spatial thinking —** The learner intentionally represents and analyzes spatial relations to make sense of a situation, identifying relevant features and constraints, and stating what is known about the configuration. The learner can construct or

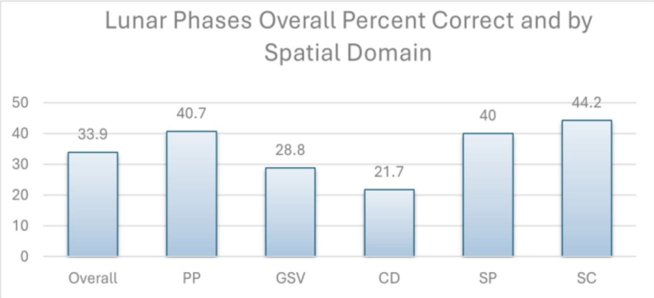


Figure 1. Lunar phases survey overall results and by spatial domain (created by the authors)

interpret spatial representations (sketches and simple models) and consider alternative perspectives.

3. **Spatial reasoning** – The learner applies principles and transformations to spatial configurations and integrates motions of bodies to predict and explain phenomena from multiple frames of reference.

This tiered structure keeps "awareness" as recognition, "thinking" as structured description and representation, and "reasoning" as application of transformations and motion to predict, solve, and explain.

RESULTS

Survey Findings

Lunar phases

The lunar phases questions that were coded as Earth-based perspective questions showed PSTs scoring 32.3% correct while the coded Space-based perspective questions showed PSTs scoring 31.3% correct. **Figure 1** shows PSTs correctly scoring 33.9% overall, 40.7% PP, 28.8% GSV, 21.7% CD, 40% SP, and 44.2% SC. PSTs scored best on those questions addressing Earth/Moon/Sun SC (44.2% correct), periodicity of lunar phases and orbit (40.7% correct), and viewing phases from various Earthly locations (40% correct). Questions that dealt with CD of the Moon for phases at different times showed the least understanding (21.7% correct).

Seasons

Of the 60 PSTs, nearly half (47.6%) scored correctly on those Seasons questions coded as Earth-based perspective. However, only 28.1% of the PSTs scored correctly on the seasons questions coded as Space-based perspective. Looking closely at the seasons data overall and by seasons domain, **Figure 2** shows PSTs correctly scoring 37.9% overall, 24.2% axis tilt, 7.2% Earth orbits Sun, 48.3% variable sunlight, 65.8% cumulative, and 38.3% Earth rotates on axis.

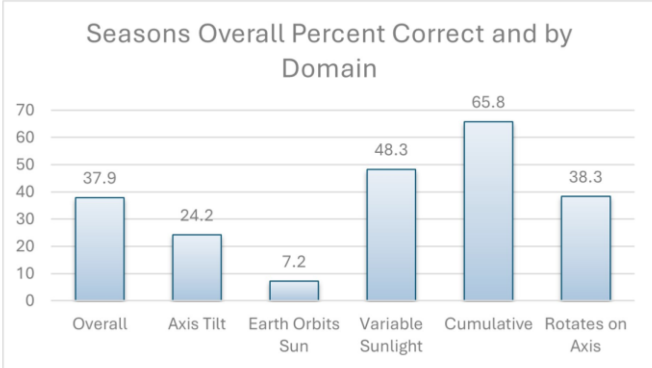


Figure 2. Seasons survey overall results and by domain (created by the authors)

PSTs performed best (65.8% correct) on those questions that combined in some fashion domains 1-3 (axis tilt, Earth orbits Sun, and/or variable sunlight). An example question illustrating this is *Which of the following explains why we experience different seasons in Kentucky throughout the year?* The next best scored domain was variable sunlight with 48.3% correct. The questions revealing the least understanding concerned the concept that Earth orbits the Sun (7.2% correct).

Interview Findings

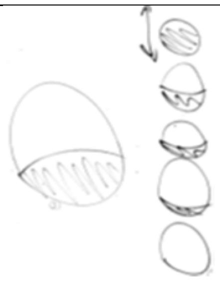
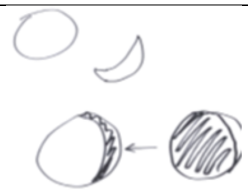
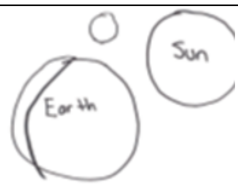
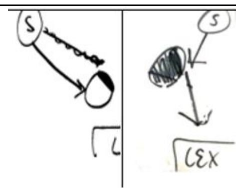
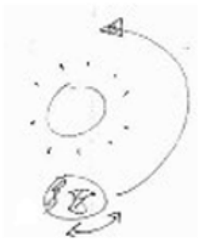
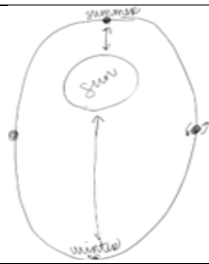
We highlight the five interviews that display the lunar phases and season's understandings of the PSTs. The interviewees were Monica, Phoebe, Debbie, Fiona, and Emma. All PSTs volunteered to be interviewed and pseudonyms were used.

Monica: When asked to illustrate lunar phases that she had observed, Monica sketched gibbous-like phases, a new Moon, and a full Moon, but no crescent shaped phases (see **Table 2**). The larger Moon she drew appears more like a lunar eclipse than a gibbous phase due to incorrect curvature of the terminator line (a line that separates the illuminated and unilluminated portion of a planetary body).

Below is an excerpt of Monica's explanation to why the Moon looks different at different times [R: Researcher].

> M: It's positioning compared to the Sun and then also even maybe potentially the Earth itself. And then by just not having enough light, I guess, shown onto it from the Sun and that's where shadows will be cast.
>
> R: Can you elaborate some more – I think you mentioned shadows.
>
> M: There's going to be an illuminated area that the light touches and there will be an area that the light doesn't touch, kind of like the Moon, I guess you could say, that would be the shadow area because the light doesn't reach that portion, so it's not going to be illuminated.

Table 2. PST's sketch of lunar phases, cause of phases, and cause of seasons

	Monica	Phoebe	Debbie	Fiona	Emma
Phases previously observed					
Illustrating cause of phases	No sketch	No sketch			
Illustrating cause of seasons					

Monica seemed to have a correct understanding that relative position of the Earth/Moon/Sun determines the phase we see. When she mentioned 'shadows will be cast', she only referred to the portion of the Moon that is not illuminated and did not indicate an Earth's shadow or Sun's shadow blocking notion.

During the seasons portion of the interview, Monica was asked why in Lexington was it warmer in the summer and colder in the winter.

> M: … It's the Earth's rotation closest to the Sun type thing … distance from the Sun, or it's closest to the Sun.
>
> R: So, when you say the distance from the Sun…why is it warmer in the summer and colder in the winter?
>
> M: … The Earth cannot get closer to the Sun. Right? Because I believe, I don't know, because it follows on the same path that kind of revolving around it. So, or yeah, I don't know … but then when the Earth is turning on its axis – I believe that's what it'd be turning on - then I think that when it's closer to the Sun, when it's turning, that's kind of how the seasons form.

Table 2 shows the drawing sketched by Monica as she explained that the side of the Earth closest to the Sun (due to the Earth turning on its axis) is when Lexington would experience summer. Monica did not mention tilt and only indicated that the Earth rotates on its axis while keeping a constant distance from the Sun.

Phoebe: Phoebe stated that she rarely looked at the Moon. When asked to sketch any way she might have seen the Moon, she drew sketches of the Moon during a full Moon phase and crescent phase (3 similar crescent shapes) as shown in **Table 2**.

> R: [after having drawn a full Moon] Would you mind drawing the other ways that the Moon can be perceived? [She draws 3 crescent shapes.] With your drawings, can you explain a little why they appear differently?
>
> P: So, this would be a full Moon [points to circle of full Moon], then the crests and, like, throughout the month they will appear differently.
>
> R: Why does the Moon look different (at different times)?
>
> P: I guess it's just how the Sun is hitting it, we portray it different [sic] on Earth.
>
> R: And do you know a little bit more about why this happens?
>
> P: I'd say it has to do with something the way the Earth is on its, like, tilt and it rotates. We just see it differently.

Phoebe seemed to understand that perspective from Earth might be a reason we see the Moon differently at different times when she claimed "it's just how the Sun is hitting it, we portray it different on Earth." However, Phoebe incorrectly followed up with the statement that it has something to do with the Earth's tilt.

For the seasons questions, Phoebe sketched a drawing of the Sun and the Earth positioned at different locations around the Sun in what appeared to be an elliptical orbit (see **Table 2**). Phoebe described this orbit in terms of how the Earth "rotates" around the Sun. She stated, "***So, here's the Sun. Here's the way that Earth rotates around the Sun. So, then summer would be here*** [position where Earth is closest to the Sun] ***because we're closer and then winter would be here because it's farther away***". Phoebe held the misconception that the Earth is closer to the Sun in the summer and concluded that would be the reason why it is warmer in the summer.

Debbie: Debbie readily drew various lunar phases and then when asked why does the Moon look different at different times, she explained:

> D: I think it is, depending on, like, where the Sun is in relation to the Earth. If the Earth is, like, if the Sun is not covering it all, then it's a full Moon, if the Sun isn't covering the Earth … if the Earth isn't covering AHHH one of them, if they're not covering each other it's a full Moon. I don't think it's right … I don't know, something like …

> R: I guess I need to better understand what you mean by covering. Can you draw the Earth and the Moon and what you are talking about there?

> D: I can try. [Debbie draws a sketch of Earth/Moon/Sun (not to SC) with the Moon positioned between the Earth and Sun in what would be considered the waxing crescent Moon phase position if observed from the Earth, see **Table 2**.] I don't think that's right … Something like they're … like kind of like a shadow, maybe the Sun and the Earth … Can I skip this question?

Debbie originally discusses that the Moon sometimes looks different due to the Sun's relation to the Earth but followed with language of Sun coverage and/or Earth coverage. Although, not to SC, Debbie's Earth/Moon/Sun sketch showed geometrically the correct orientation for a waxing crescent Moon phase (if observed from Earth), but she never called it that phase. She followed up by explaining her covering language to be something like "a shadow, maybe the Sun and the Earth". Debbie requested to end this portion of the interview.

When describing cause of seasons, Debbie modeled in both 2D (on paper as shown in **Table 2**) and in 3D (models) how the Earth spins on its axis. She stated:

> D: The Earth spins on the axis. And the Earth is spinning and the Sun goes around here [modelling the Sun orbiting the Earth]. And the Sun's up here, and we're up here when it is summer … This would be summer because we're close to the Sun. [She points to the side of the Earth facing the Sun].

> D: [Debbie rotates Earth counterclockwise on its axis so that Lexington is on opposite side of Earth from the Sun]. This is winter.

Debbie reveals multiple misconceptions regarding her Season's understanding. Firstly, she believed that the Sun orbits the Earth; secondly, like Monica, believed that the side of the Earth closest to the Sun (due to the Earth turning on its axis) is when Lexington would experience summer and when Lexington was not facing the Sun would be winter.

Fiona: When Fiona sketched Moon phases she recollected observing, she drew a full, a crescent, and a gibbous Moon, although she did not name them as such (see **Table 2**).

Below is an excerpt of Fiona explaining why the Moon looks different at different times:

> F: So if I was right here, and I was looking up at the Moon, like I said, I always assume it's going to be right up here. [Stating Moon is always found in the same location.] Now this is the part that it could be wrong, but I think it's okay if I'm wrong. I think the Sun is going to be like here…. And then depending on where I am, and how much Sun is coming through, is what I would see. But I don't know exactly like what Moon phase I would see.

> R: When you say the Sun is coming through, what do you mean?

> F: From the Sun and the energy, I guess, but specifically the light

> R: But when you say "through" you mean?

> F: Around and probably, yeah, around.

> R: Okay. So, but you're saying for this one [pointing at the Moon Fiona drew between the Sun and the Earth in her cause of Moon phase sketch in **Table 2**], you're not sure, what Moon phase?

> F: I think it'd be a full Moon in the picture I drew but it could be wrong.

> R: If say that were a full Moon, where would the Moon be for us to see something that looks like that [pointing to her crescent Moon phase she had sketched].

> F: Here, and then for the flipped version, but I don't even know if that's actually a thing, it would be here and then that would be covered. Does that make sense?

> R: Okay, so how would that be covered? Like covered with what?

> F: That's a good point. I don't know. I guess it would not. It would be covered but I'm not sure what is covering it. But that's like what I would see from that point.

In **Table 2**, under Fiona's sketch of Earth/Moon/Sun geometric positions that would result in viewing a full Moon or a crescent Moon from an Earthly perspective, Fiona first sketched the Earth (farthest left circular figure) and the Sun (bottom right figure with Sun's rays shown with squiggle lines). She sketched the Moon between the Earth and Sun. When asked what Moon phase we would observe with the Moon in that position, Fiona stated that she was not sure, but it was probably a full Moon. She was then asked to show where the Moon would be located for us to observe a crescent Moon, and she drew a crescent Moon on the lower left side and then she said the flipped version would be on the other side (the Moon that is shaded except for a small patch facing away from the Sun). She indicated that the Moon was covered except for the small patch. When asked what the Moon was covered by, Fiona indicated that she did not know. Fiona did not seem to be aware that the illuminated side of the Moon should be facing the Sun.

For the seasons portion of the interview, Fiona was asked why it was warmer in summer and colder in winter in Lexington. She replied:

> F: Because of our axis, and like how we are, not rotated, but positioned, I guess. And where we are in relativity to the Sun …

Fiona's initial answer suggested that she believed the position of Earth relative to the Sun and Earth's axis has something to do with it. She was asked to draw a sketch to illustrate her meaning. She drew the Earth and explained that it was tilted on its axis at 45°. She then drew a half circle to illustrate the Sun, explaining that Earth "rotated" around the Sun [gesturing with her hands an orbital movement]. She elaborated further.

> F: And it is our summer when we are directly in front of it [Sun], and our rotation is closest to the Sun. And that is why Australia would have winter at that time. [Drawing stars to show that Australia was located on the opposite side of Earth from Lexington.] But, if you flipped it [shows rotation with her hands], then they [Australia] would have summer, and we [Lexington] would have winter at Christmas [and Australia would have Christmas during their summer].

Fiona believed that Earth's rotation on its axis caused the seasons rather than the combination of Earth's tilt on its axis and its orbit around the Sun.

Later in the interview, the researcher asked questions to clarify Fiona's thinking about the causes of seasons and the motion of Earth and the Sun.

> R: Okay, so does anything move? Like, does the Sun move, or does the Earth move, or both?

> F: Okay, well, I don't know about the Sun. I know the Earth moves. It rotates like this [demonstrates motion of rotation on an axis], as well as like this [demonstrates orbiting around the Sun]. I know our Moon moves around us, but I don't think the Sun moves, but I could be wrong. And then yeah, we rotate around the Sun ... [uses the 3D models to show Earth orbiting Sun].

> R: So, you said that the Earth moves around the Sun. How long does it take to go around this?

> F: It's a month? I don't know. I think a month.

> R: And does that affect anything about the seasons?

> F: Oh, my immediate reaction says yes, but I don't think so.

Like Monica and Debbie, Fiona believed that Lexington is warmer in summer because of the closer proximity of Earth to the Sun due to its rotation (Earth's rotation on its axis) toward the Sun. As the Earth rotates away from the Sun in the fall it becomes cooler until Lexington experiences winter when that side of Earth has rotated to be directly opposite the side facing the Sun. It is interesting that Fiona understood that Earth orbits the Sun, but she did not believe this movement affected the seasons experienced on Earth. Further, she believed the path Earth follows around the Sun would take about a month to complete. Although she did not mention a time frame for the complete Earth rotation on its axis, her answer suggests the rotation would take one year to complete. Visualizing seasons in this manner also illustrates PSTs' lack of understanding the cause of day and night.

Emma: When asked to sketch various lunar phases, Emma recollected observing, she made some unusual drawings (shown in **Table 2**). She sketched the Moon like a pie chart shading in various sections of a circle that represented the Moon. Sections appeared to be 1/8 of a pie shaded, to half of a pie, to ¾ of a pie, to fully shaded. The excerpt below illustrates how she spoke of these lunar phase representations.

> R: So, when you have it, like where you shade it? What does that mean?

Figure 3. Emma's sketch of the Sun orbiting 5 planets including Earth with its Moon (created by the authors)

> E: It's like the way that it's tilted. And so, it's covered by the Sun, like, so that the light doesn't get to it, and you can't see it?
>
> R: Okay, so the, the white part is the part that the light can get to?
>
> E: Yeah.

It seemed Emma was saying that the Moon was tilted and somehow this tilt did not permit the light to reach portions of the Moon. The white portion of the Moon was the part that the light could reach.

Emma was shown pictures of a waxing crescent and a waxing gibbous Moon. Emma was asked to sketch the Earth/Moon/Sun arrangements for the waxing gibbous phase and the waxing crescent phase. **Table 2** illustrates Emma's sketches. The left-hand sketch showed Emma positioning the Moon between the Sun and Lexington (on Earth). She wanted to show how part of the Moon was not illuminated – so she marked out one of the Sun's rays so that the sunlight was not illuminating that part of the Moon. For the waxing crescent sketch (right-hand drawing), Emma did show a somewhat accurate Earth/Moon/Sun arrangement (not to SC) to create a waxing crescent Moon as seen from Earth. She explained how the shaded part of the Moon would be the part that a person would not see. Both drawings were arranged where the Moon was between the Sun and Lexington/Earth. Emma was asked if the Moon moves or if anything moves; she followed with the sketch shown in **Figure 3** illustrating the Sun (large circle on left) orbiting five planets where the third planet from the Sun was Earth with Earth's Moon next to it.

In terms of cause of seasons understanding, Emma, like Monica, Debbie, and Fiona, shared the misconception that Earth's rotation on its axis causes the seasons. This was apparent when she was asked why it is warmer in Lexington during the summer. She explained it was the position of the Sun and then elaborated on her thinking.

> E: The location of the Sun.
>
> R: What about the location of the Sun?
>
> E: The closer it is to us ... So, the closer it is shining ... The Earth rotates, and the Sun is shining ... The Earth is moving, and the Sun is [shining] down on us. It is winter [turns her hands to show Earth rotated away from the Sun] when we are farthest from the Sun, and it is summer when we are closest to the Sun.

When asked to draw a picture to illustrate her thinking, Emma had difficulty drawing the sketch in a way that the researcher could understand her thinking. The researcher provided Emma with a 3D model of the Sun and two 3D Earth models, one positioned at an upright, 90° position, and a second model positioned with the axis tilted at an angle at 23.5°. Emma selected the tilted Earth model and Sun model and inserted a small piece of a toothpick to represent Lexington in the Northern Hemisphere. **Table 2** illustrates how Emma modeled causes of seasons for Winter and Summer in Lexington. Although she arranged the 3D models to show that the Northern Hemisphere was tilted toward the Sun, Lexington was positioned on the side not facing the Sun (refer to the bottom sketch of Emma's season drawing). Emma identified this arrangement as Winter. Next, she moved the Sun model so that Lexington was facing the Sun with the Earth tilted away from the Sun. Emma called this position, Summer for Lexington (see the top sketch in Emma's cause of season representation in **Table 2**).

It is curious that during the Moon phases portion of the interview, Emma had drawn the Sun orbiting all the planets, but during the seasons discussion she stated that the Earth moved around the Sun, even though she moved the Sun model around the Earth as she demonstrated winter in Lexington.

Summary of Interview Findings

We focus on evidence of asset spatial thinking towards understanding the cause of lunar phases and the cause of season for the five PSTs interviewed. **Table 3** shows features necessary for students to reach a scientific understanding of cause of lunar phases (Sun illuminates half of Moon, Moon orbits Earth, Geometric orientation of Earth/Moon/Sun determines Earthly viewed phases). Only Monica, Fiona, and Emma displayed at some point in their interviews some knowledge that relative positions of the Earth/Moon/Sun determined what phase would be observed from Earth. Monica did so as she described the Moon's position compared "***to the Sun and then also even maybe potentially the Earth itself.***" Fiona goes one step further by illustrating the Moon's orbital motion and the positionality of the Earth/Moon/Sun for various phases (crescent and full Moon) – but incorrectly calls the new Moon phase a full Moon and incorrectly illuminates the crescent Moon phases (as shown in **Table 2**). Emma also seems to have a sense that it is the

Table 3. Evidence of asset spatial thinking towards understanding the cause of lunar phases or cause of seasons

Conceptual features	Monica	Phoebe	Debbie	Fiona	Emma
Sun illuminates half of Moon	N	N	N	N	N
Moon orbits Earth	N	N	N	Y	N
Geometric orientation of Earth/Moon/Sun determines Earthly viewed phases	Y	N	N	Y	Y
Earth rotates on its axis	Y	Y	Y	Y	Y
Earth's axis is tilted	Y	Y	Y	Y	Y
Earth orbits Sun	Y	Y	N	Y	Y
Earth experiences variable Sunlight	N	N	N	N	N

Earth/Moon/Sun orientation that determines each phase we see. She correctly illustrates what could be the waxing crescent phase while incorrectly illustrating the waxing gibbous phase (see **Table 2**). None of the PSTs illustrated that from a Space-based perspective, the Moon will always be half illuminated and only one PST (Fiona) stated that the Moon orbits the Earth.

Table 3 shows the three features necessary to understand the cause of seasons (Earth's axis is tilted, Earth orbits the Sun, and Earth experiences variable sunlight). We also purposefully included Earth rotates on its axis, which is the feature to explain cause of day and night. All PSTs mentioned at some point in their interview that the Earth's axis is tilted, but no one linked it to a key feature towards explaining cause of seasons. Phoebe mentioned Earth's tilted axis as an explanation for cause of lunar phases. All PSTs, except Debbie, mentioned or illustrated at some point during their interview that the Earth orbits the Sun; however, Emma also stated that the Sun orbits five planets in the solar system including Earth (**Figure 3**). No one discussed the effect of variable sunlight towards an explanation of cause of seasons.

Focusing on the PSTs' asset understanding, as shown in **Table 3**, illustrates the fragmented nature of their knowledge, similar to diSessa's (2018) KiP model. All PSTs displayed episodes of spatial awareness (e.g., in their Moon phase sketches) and spatial thinking (e.g., in their descriptions of their models). No PST progressed to the level of spatial reasoning where they were able to sketch Earth/Moon/Sun configurations and describe the motions involved to explain cause of phases – the view of the Moon from an Earth-based perspective during various positions in its orbit around the Earth. Similarly, no PST progressed to the spatial reasoning level to sketch Earth/Sun configurations and explain how the tilted orientation of the Earth along with its yearly orbit around the Sun were the reason for their Earth-based observations of seasons experienced on Earth.

DISCUSSION

This study examined PSTs' spatial awareness of astronomical phenomena from both Earth-based and Space-based perspectives. Regarding RQ1, performance patterns suggest that PSTs' spatial understanding is fragile across perspectives and particularly vulnerable when tasks require mental transformation into a Space-based frame of reference. On the lunar phases assessment, approximately one-third of PSTs answered correctly for both Earth-based (32.3%) and Space-based (31.3%) items. The similarity in performance indicates that even when questions are grounded in the more familiar Earth-based viewpoint, PSTs struggled to accurately coordinate Earth/Moon/Sun relationships.

In contrast, results for seasons revealed a clearer divergence. PSTs performed better on Earth-based items (47.6% correct) than on Space-based items (27% correct). This pattern supports the interpretation that Earth-based questions may allow PSTs to draw upon experiential or phenomenological reasoning (e.g., temperature changes and daylight length), whereas Space-based questions require coordinated spatial transformations—mentally visualizing axial tilt, orbital motion, and the angle of solar incidence. The substantially lower performance on Space-based items suggests limited facility with perspective-taking and dynamic spatial reasoning.

Findings from RQ2 further illustrate the nature of PSTs' spatial thinking. Interview data revealed that participants such as Phoebe, Debbie, and Fiona could sketch recognizable lunar phases, demonstrating some competence with static 2D representations. However, their explanations exposed incomplete or pieces of knowledge leading to incorrect causal reasoning. Fiona's explanation that phases occur because of "how much Sun is coming through" similarly suggests a partial but unintegrated understanding of illumination. These responses indicate that PSTs may possess spatial awareness in the form of emerging representational skills (e.g., drawing observed phases) without fully developed mental models capable of supporting accurate causal explanations that draw connections across 2D and 3D models and their Earth-based observations. Their success in drawing familiar representations alongside difficulties explaining underlying mechanisms is consistent with diSessa's (2018) KiP perspective that knowledge can be locally productive while remaining insufficiently connected across contexts.

Taken together, the quantitative and qualitative findings suggest that PSTs' spatial reasoning is often compartmentalized: they may reproduce familiar images yet struggle to mentally manipulate celestial bodies in 3D space across time. This disconnect aligns with prior research showing that misconceptions in astronomy persist even when learners can produce correct diagrams (Galperin & Raviolo, 2019; Plummer et al., 2014; Sağdıç & Şahin, 2023). The results highlight the importance of explicitly addressing perspective-taking, dynamic modelling, and the coordination of multiple frames of reference within teacher preparation.

Overall survey scores of 40% or below, coupled with interview evidence of persistent misconceptions, underscore the need for more intentional development of spatial reasoning within elementary teacher preparation. In particular, findings point to the importance of incorporating sustained space-based interventions that require PSTs to shift perspectives, physically model Earth/Moon/Sun systems, and engage in iterative mental motions and simulations (Plummer, 2016; Wilhelm et al., 2018). While misconceptions may persist even after instruction, as noted by Tsai and Chang (2005), deeper engagement with 2D and 3D spatial representations can move learners toward more sophisticated, though still evolving, understandings.

Recent practice-based and modelling-focused interventions (e.g., Galano & Testa, 2025; Türk & Kalkan, 2018) reinforce that strengthening foundational astronomical knowledge must occur alongside the development of spatial visualization skills.

CONCLUSION

Echoing physicist Wolfgang Pauli's reflection that deeper understanding often involves "misunderstanding at a deeper level," this study identifies a critical starting point rather than an endpoint. From a KiP perspective (diSessa, 2018), the challenges PSTs encounter with astronomy concepts are not simply incorrect beliefs but difficulties in coordinating multiple knowledge resources about geometry, motion, and observational perspective into a consistent explanatory framework. The goal is therefore not merely the production of correct answers, but the development of increasingly coherent and coordinated mental models that integrate geometry, motion, and perspective. This aligns with the development of spatial reasoning—the highest tier of spatial knowledge—which involves applying transformations to spatial configurations and integrates motions of bodies to predict and explain phenomena from multiple frames of reference. Developing PSTs' ability to mentally rotate, transform, and coordinate celestial bodies in both Earth-based and Space-based frames is essential if they are to teach these concepts with clarity and conceptual integrity. Equally important is fostering the capacity to visualize the Moon, Sun, sky, and their motions from multiple worldly perspectives (Mulholland & Ginns, 2008; Wilhelm et al., 2008). Such experiences can support the reorganization and refinement of existing knowledge pieces into more stable and scientifically productive explanatory structures. Collaborative studies involving countries from both the Northern and Southern Hemispheres and Equatorial regions, such as the College MOON Project (Mulholland & Ginns, 2008; Wilhelm et al., 2008), may further facilitate development within the SP domain (Earth-based perspective) by providing opportunities for learners to activate and coordinate knowledge resources across diverse observational contexts. Future research should examine longitudinal impacts of explicit spatial interventions and investigate how improvements in spatial visualization translate into classroom practice and student learning outcomes.

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