Solving astronomy problems can be limited by intuited knowledge, spatial ability, or both

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Abstract

Solving problems in a visuospatial domain, such as astronomy, may require not only knowledge about the phenomena within the domain but an ability to instantiate knowledge spatially to generate solutions as well. Spatial ability assessments and interviews of undergraduates show that problem-solving ability can be limited regardless of the scientific accuracy of an individual's causal beliefs about astronomy. Spatial ability was found to be somewhat positively correlated with problem solving performance, regardless of the causal beliefs an individual holds. Providing external aides (colored balls) for help with spatial reasoning improves performance, a further sign of the influence of spatial ability on problem solving. The specific causal explanation for a phenomenon an individual believes may itself be related to spatial ability. For learners to better understand and apply scientific explanations of astronomy, it may be necessary to provide spatial skills training as a component in instruction.

The cognitive aspects of causal beliefs of natural phenomena are particularly important for science education: many explanations are only partially correct from a scientific perspective, or they may include entities and relationships that are not considered to be scientifically relevant at all. If one of the primary, universal goals of education is to train individuals to be able to solve problems within specific domains of knowledge, then the causal understanding a student possesses of some phenomenon and his or her ability to apply it to novel problems are critically important.

Intuitive causal models

Science educators and cognitive scientists have repeatedly found students to have preexisting conceptions of basic, natural phenomena before receiving formal instruction about them (Driver, Guesne, & Tiberghien, 1985). Often these pre-science conceptions deviate from scientific explanations, and students resist changing these pre-science conceptions during instruction, which alters the learning experience as students actively reinterpret classroom instruction in support of their conceptions rather than abandoning them for more scientifically accepted explanations (Driver & Easley, 1978; Wandersee, Mintzes, & Novak, 1994). They are powerful enough to be held by instructors as well (Wandersee et al., 1994).

A growing body of literature points to larger structures than individual misconceptions as the cause for non-scientific explanations of natural phenomena. Researchers investigating misconceptions gradually came to acknowledge the problem of the term "misconceptions" as mistakenly implying a negative or useless thought or belief. Others acknowledge the larger perspective behind some or all non-scientific conceptions, referring to the phenomenon as "alternative frameworks" (Nussbaum & Novick, 1982). Cognitive scientists who investigate concepts as units of knowledge now discuss concepts as pieces of larger networks of concepts linked by their coherence (Murphy & Medin, 1985; Ross & Spalding, 1994). Child development researchers have observed how children make inferences from simple associations to larger generalizations (Mandler, 2000), and sometimes describe the process as one of discovery, much like the nature of scientific discovery (Gopnik, 1996; Brewer & Samarapungavan, 1991), referring to the non-scientific beliefs as "naive theories" (Wellman & Gelman, 1992). Philosophers of science have recently turned to consider the cognitive aspect of formal, scientific theories, or the human understanding of formal theories (Gopnik & Meltzoff, 1997; Brewer, 1999).

Larger structures of non-scientific causal beliefs may explain the resiliency of misconceptions. Theories, as a form of mental representation, have been described as a causal set of interrelated abstract entities that a person can mentally use to simulate some event for prediction and problem solving (Gopnik & Meltzoff, 1997; Brewer, 1999). These models are often based on insights or intuitions, not rigorous testing and study, like formal theories, and so they might be best thought of as intuitive causal mental models. When solving a problem, the solver instantiates a set of concepts and their causal relations to model the problem space and generate a solution or make a prediction.

Some domains of knowledge have characteristics that appear to lend themselves to intuitive causal models. What characteristics these might be, and whether they are universal to all domains of knowledge, are not well established. However, likely characteristics are those phenomena that (a) are the result of multiple interacting factors (b) which are only partially observable by the untrained observer, and (c) with relationships between entities that are unusual or are nonlinear. [1]

Assessing adult beliefs about astronomy

An on-going project has uncovered and established the structure of intuitive causal models about basic observational astronomy commonly held by undergraduates using an extensive short-answer questionnaire about basic observational astronomy (Brewer & Rudmann, 2002). The questionnaire uses a short-answer format to elicit factual knowledge, explanations, and problem solving ability. Questions that test for factual knowledge, such as "When it is summer in the U.S. what season is it in Australia?" may result in a response that a student used a causal model to generate, but most likely the response would be the result of recalled information. Items that ask for explanations, such as "What causes the seasons?" require the student to express in written form the concepts and relationships he or she believes are important to satisfactorily show causation.[2] Other items pose novel

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[1] Of course, these characteristics be true for most, if not all, natural phenomena.

[2] How an individual decides what constitutes a satisfactory explanation is unclear.

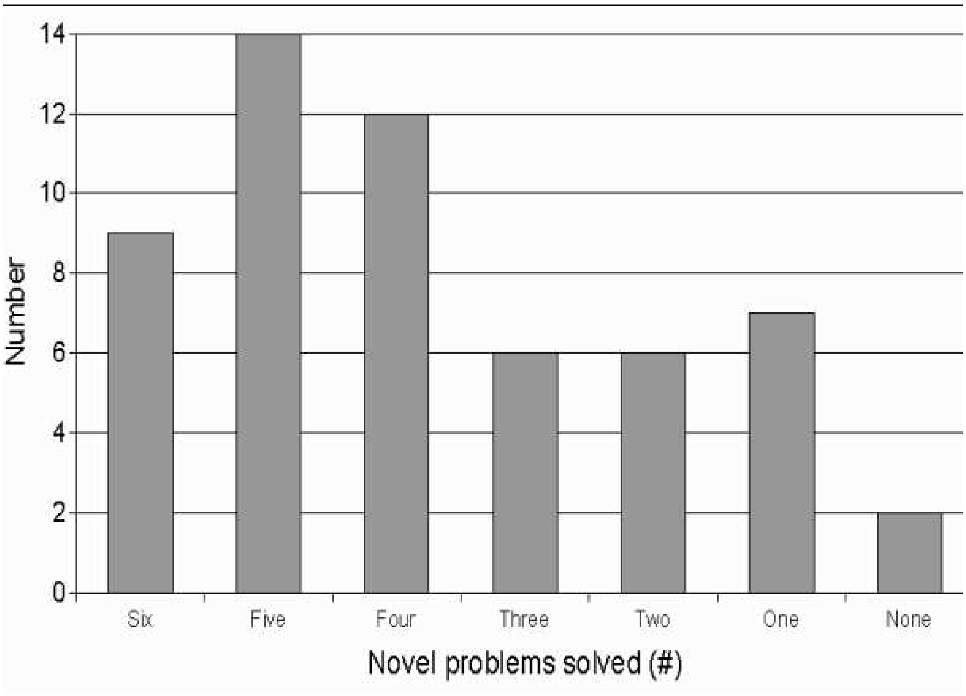


Figure 1. Number of participants who provided heliocentric, Earth-rotation explanation of the day/night cycle by the number of novel day/night cycle problems solved (Brewer & Rudmann, 2002).

problems, inviting the application of causal knowledge to solve the problem. Because the problems were intentionally written to be open-ended, any causal model can be used to generate an answer.

Performance limitations

Surprisingly, a number of problems are answered incorrectly given the student's own causal belief; that is, their answers are often inconsistent with their own understanding of the phenomenon, though nearly all participants possess an intuited or scientifically-accurate model which could be used to generate plausible, consistent answers to all of the questions. While 76% of the 74 participants provided a heliocentric explanation for what causes the day/night cycle, the ability of those students to apply that knowledge and solve a series of six novel problems ranged from all six to zero (see Figure 1).

From a cognitive perspective, one's ability to apply a body of knowledge may be limited by his or her capacity to simulate an answer to a novel problem, regardless of the scientific accuracy of his or her knowledge of the domain. Given that mentally modeling some phenomenon is a cognitive act that requires computation, a domain that is very spatial in nature, such as astronomy, will likely require spatial reasoning ability to be able to compute some answers, regardless of how scientifically accurate an individual's knowledge of the domain is. Generating the mental problem space within a visuospatial domain to solve problems may be constrained or limited by the individual's spatial ability, which has been recognized by educators within earth science as a critical but virtually unresearched factor (Ault Jr., 1994).

However, incomplete and incorrect answers on a questionnaire could simply be a byproduct of the method of assessment. Participants may not have demonstrated their true performance limits, if any, on a questionnaire. A structured interview is likely to produce a better assessment of any limitations in problem-solving than a paper-and-pencil test.

Current study

This study investigated whether performance limitations of problem solving exist within the domain, controlling for prior knowledge about the domain, and assessed whether the performance limitations may be due to spatial ability.

Method

Participants

Eighteen University of Illinois students participated for course credit. The mean age was 23.6 years, and 83.3% were female.

Measurements

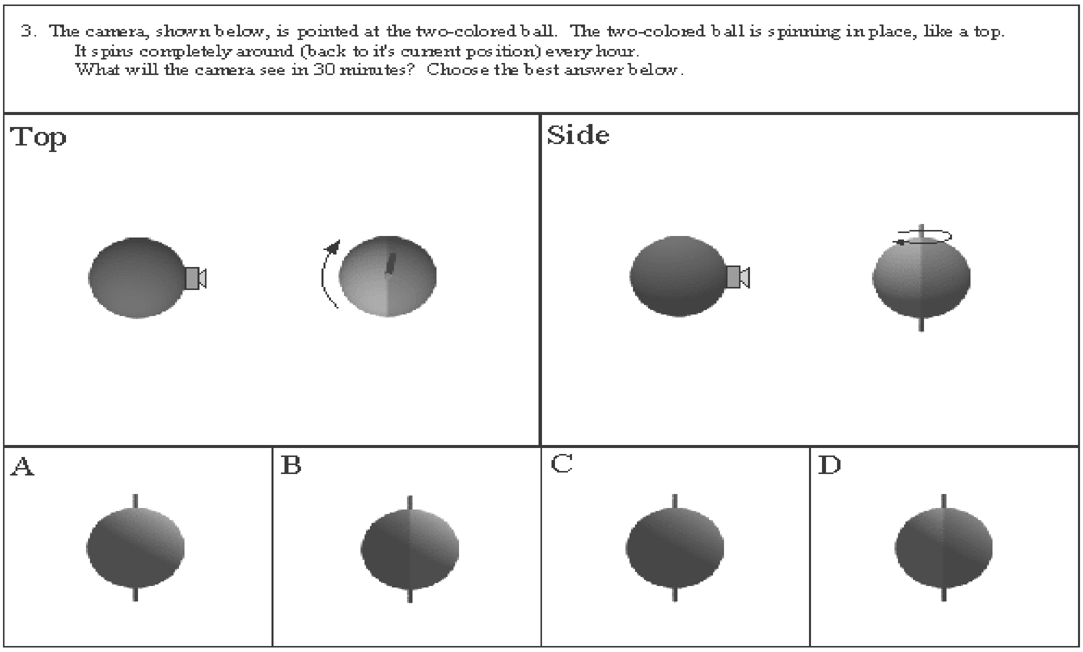
Three tests and a structured interview assessed the participants' spatial ability, knowledge of astronomy, and ability to solve astronomy problems.

For spatial ability, two tests were used: the Cube Comparison test was used to assess general spatial ability (Educational Testing Service, 1963), and the Astronomy-based Geometry (AG) test. Designed specifically for this study, the AG test contains 21 items containing scenes of full-color, computer-rendered spheres that appear three-dimensional. Each item provides with a top-down and side view of a scene containing spheres and must mentally integrate the two to create a mental image of the three-dimensional scene. The test-takers evaluate the scene from the perspective of the camera and choose from four alternative views, like photographs, in a multiple-choice format. Different items test for different spatial skills that are unique to the astronomy domain, such as rotation (spin), revolution, tilt, occlusion, light and shadow, and combinations of those factors (a sample item is shown in Figure 2). The total number correct responses constitutes the score.

A short questionnaire adapted from Brewer and Rudmann (2002) assessed the participants' basic knowledge of astronomy using short-answer essay questions. The responses on the questionnaire become the basis for the structured interview.

The structured interview begins by asking participants to describe the basic movements in the solar system and to explain what causes the day/night cycle, seasons, phases of the Moon, and eclipses. After each explanation, the participants provide a confidence rating on a 5-point scale to indicate their certainty about the scientific accuracy of their explanation. Then, participants answer novel problems related to the phenomenon they just explained. For example, one set of items tests the participants' ability to reason about day and night in relation to the concept of Earth's 24-hour spin on its axis:

> "Suppose you were out at night, during the winter months, and we stopped the Earth from spinning (rotating) on its axis, and left everything else the same.



3. The camera, shown below, is pointed at the two-colored ball. The two-colored ball is spinning in place, like a top.
It spins completely around (back to it's current position) every hour.
What will the camera see in 30 minutes? Choose the best answer below.

Figure 2. A sample item from the Astronomy-based Geometry test.

> Over the course of a year, what changes, if any, would we see in (a) the stars, (b) the Sun, (c) the day/night cycle, (d) the seasons?"
>
> "Suppose we sped up the Earth so that it spins (rotates) around on its axis once each hour (current Earth units) and left everything else the same. Over the course of a year, what changes would we see in (a) the stars, (b) the Sun, (c) the day/night cycle, (d) the seasons?"

To assess the potential benefit of external aides for solving the astronomy problems, the interview is repeated once. Initially, participants are kept from using their hands or any other aides to help them solve the problems. Colored balls are provided during the second time through the problems and participants are encouraged to use whichever balls they find helpful to solve the problems.

During the interview, the interviewer (the author) attempts to prompt the participants to clarify their answers as much as possible, without leading responses toward more scientifically correct responses or challenging responses for possible inconsistencies. The role of the interviewer in this study is to elicit evidence of knowledge and reasoning ability, not to encourage more scientific answers. When time permitted, the interviewer would ask a series of follow-up questions that prodded the participants for inconsistencies in their explanations, particularly those inconsistencies that the participants knew themselves but had forgotten, to see how the participants would react.

Responses from the interview are coded by the causal explanation provided, and answers to problems are scored by their consistency to their own explanation.

Procedure

Participants first receive the Cube Comparisons test, then the astronomy questionnaire, and then the structured interview. The structured interview is digitally recorded for data analysis. Participants take the AG test last. While it is possible that the interview may bias the AG test results, a lengthy exercise in spatially manipulating objects would alter the nature of the interview and problem solving by providing practice in spatial reasoning.

Results

Responses from the questionnaire and explanations provided during the interview were coded by causal model type for each topic area. Answers to problems posed to the participants during the interview were scored as correct if they were congruent with their explanation of the phenomenon. Data from the day/night cycle and seasons topic areas are discussed below.

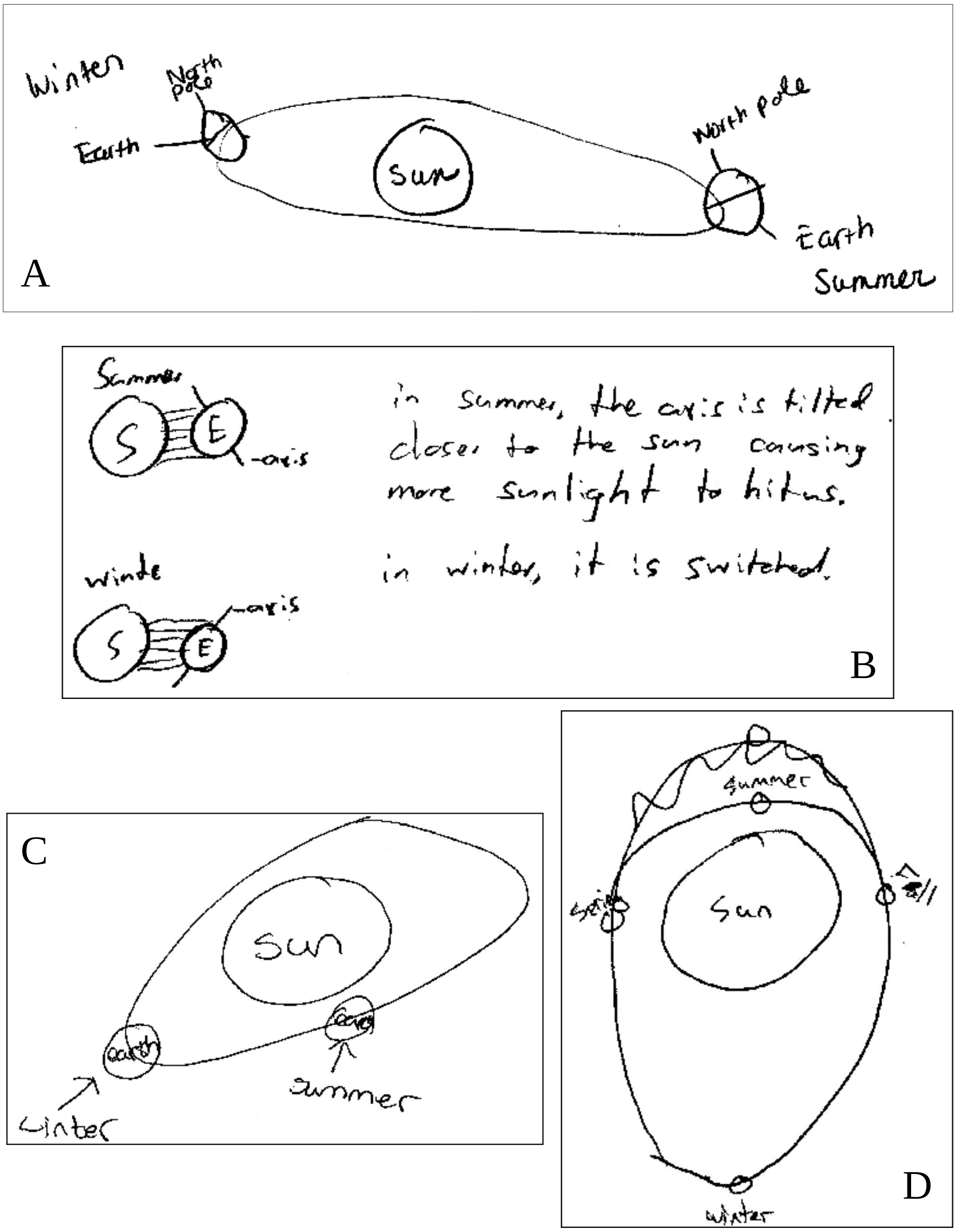
Descriptions of causal models

For the day/night cycle, both heliocentric and geocentric explanations are common. Heliocentric explanations include the Sun as an object fixed in space, and the Earth rotating on a 24-hour basis, with daytime in a particular geographic region caused by exposure to sunlight as the Earth spins. Geocentric explanations include the Earth as an object fixed in space, possibly rotating on its axis, while the Sun orbits the Earth on a 24-hour basis. Either explanation may include the Moon as an object orbiting the Earth opposite the Sun, as component of nighttime. In the heliocentric version of this extra component, the Moon will orbit the Sun outside the Earth, like a planet.

Frequently participants made geocentric drawings on the questionnaire to explain the day/night cycle, but would consistently use heliocentric explanations during the interview. Possibly participants find geocentric explanations easier to provide in drawings, ignoring the misleading nature of the answer.

For the seasons, four causal explanations were found. In the “Fixed Tilt” model, the participant describes the Earth as having a tilt that is fixed in one absolute direction as Earth travels around the Sun in a yearly path. A typical drawing from such a participant is included in Figure 3A. The tilt in combination with the Earth’s position the orbital path are jointly the primary cause of the seasons and of the models discussed in this paper, is the most scientifically accurate. Participants give different accounts of the heating mechanism that the tilt provides. Some consider it to be a matter of the angle of sunlight, change in length of day, or a matter of being physically closer to the Sun, causing a change in the heat intensity of sunlight.

The “Wobbly Tilt” model is a degraded version of the Fixed Tilt model. Some participants understand that the tilt of the Earth is critical for causing the seasons and that the tilt provides a change in relationship between the hemispheres and the Sun as the Earth travels around the Sun on a yearly path, but they do not lock the tilt in one absolute direction as the Earth travels around the Sun. That is, the tilt of the Earth is not fixed



in summer, the axis is tilted closer to the sun causing more sunlight to hit us.

in winter, it is switched.

Figure 3. Sample causal model drawings: (a) Fixed Tilt, (b) Wobbly Tilt, (c) Elliptical Orbit, version A, (d) Elliptical Orbit, version B.

but changes as the Earth moves around the Sun. Where the Earth is in its orbit around the Sun and the tilt of the Earth are different factors that are not directly related. In text and drawings these individuals will not provide an orbit for the Earth to traverse around the Sun since it is not a critical factor for the seasons, as shown in Figure 3B. During interviews, they will demonstrate this model by intentionally moving the tilt of the ball they have chosen to represent Earth as it travels around the Sun to bring one geographic location on "Earth" closer and further from the Sun.

In the "Elliptical Orbit" model, participants explain the seasons as primarily the result of a large-scale distance change between the Earth and Sun, with the Earth moving closer to the Sun for summer and then further away for winter in a heavily elliptical orbital path. Two variations exist: some will place the Sun in the center of Earth's path, as shown in Figure 3C, and some will place the Sun at one of the focal points of the elliptical orbit, as shown in Figure 3D. Besides being scientifically inaccurate, these models are inconsistent with the participants' own knowledge. In the first variation, four seasons would occur twice a year, which is not a common belief. In both variations, the entire planet experiences one season at a time, which most participants know is untrue: on the questionnaire, 17 out of the 18 participants stated that Australia experiences a different season from the U.S.

One participant demonstrated a "Quantum Orbit" model. The Earth orbits the Sun in a circular path on a daily basis, and during summer, it circles the Sun much closer than in the winter. It was not clear to this participant how the Earth switched from one orbital path to the other. While only one participant held this particular belief, it has been found in prior research as well (Brewer & Rudmann, 2002). Both individuals' models were geocentric in nature; there does not appear to be a naturally-occurring heliocentric version of this model.

Consistency in explanations

Some of the participants were not consistent in their explanations of the day/night cycle or seasons over the course of the interview. When the participants were asked to demonstrate their explanations using the colored balls, they encountered difficulties with their explanations and would then switch to another explanation. Because there were relatively few participants did this (three participants abandoned their earlier explanations for a total of four times across the two topic areas), there is not enough data to fully consider them as a separate group. But they did demonstrate some differences from the remainder of the participants in problem-solving performance. As shown in Table 1, participants who changed their explanations performed much worse than the remainder of the group during the first attempt and second attempts. Interestingly, the mean confidence ratings did not change over the course of the interview for these participants, and the new explanation that they arrived at was not always more scientifically accurate than the one they discarded. For example, one participant began the interview providing a heliocentric explanation of day/night and then regressed to geocentric when provided with colored balls.

Because of the reduced performance of these participants, their data are excluded from any further analyses presented in this paper.

Table 1: Number of Individuals By Consistency of Their Explanations and Problem Solving Rate.

			Percent Correct	
Topic Area		Count	Time 1	Time 2
Day/Night	No Change	16	57.5	59.5
	Changed	2	29.2	33.3
Seasons	No Change	16	75.0	77.5
	Changed	2	50.0	75.0

Spatial ability and problem solving

For those participants who did not undergo a change in their explanations during the interview, their ability to solve novel problems for either topic area was somewhat reliably correlated positively with general spatial ability, $r = .464$, $p = .089$. This positive correlation existed for both the day/night cycle problems, $r = .337$, $p = .08$, and for the seasons problems, $r = .456$, $p = .077$.

Another indicator of the influence of spatial ability on problem solving performance was seen via the enhanced performance of the participants when using colored balls, as shown in Table 2. The majority of the participants were more likely to produce answers to the problems that were congruent with their explanations of the phenomenon when using the external aides as tools to reason with.

Causal models and spatial ability

Unexpectedly, the causal model that the participants use to explain the seasons appears related to spatial ability. The Cube Comparison score of general spatial ability was highest for those who use the Fixed Tilt model, $x = 31.0$, and lower for the participants with the Wobbly Tilt model, $x = 12.8$, and lowest for the participants with the Elliptical Orbit model, $x = 9.2$, $F(2, 11) = 4.051$, $p = .048$. The participants' scores on the AG test varied by model as well, from a mean of 19.5 for the Fixed Tilt participants to 8.5 for the Wobbly Tilt participants to 9.8 for the Elliptical Orbit participants, $F(2, 11) = 11.663$, $p = .002$. This raises the possibility that the explanation that participants find coherent and useful may be partially determined by their spatial ability.

Table 2: Percent of Participants By Performance Change With Use of Colored Balls By Topic Area.

	Change	Percent	Mean Performance Change
Day/Night	Improved	53.3	+1.9
	None	20.0	
	Worsened	26.7	-2.0
Seasons	Improved	28.6	+1.5
	None	57.1	
	Worsened	14.3	-2.0

Discussion

The promise of this exploratory research lies in better understanding the nature of cognitive processing about scientific domains that are visuospatial in nature. Learning the scientific explanations within these domains may be restricted by spatial ability, and as this study shows, spatial abilities may be a factor that limits or restricts a student's ability to instantiate knowledge and produce a solution to a problem. If problem solving in these domains are constrained by spatial ability, then learners who are low in spatial ability will require a different form of instruction, possibly in the form of spatial skills training.

If stable trends in knowledge and spatial abilities can be identified, like "cognitive profiles," then several methods of instruction could be developed to better adapt to each student's cognitive deficits in the classroom. For example, a different instructional approach would be warranted if a student's cognitive needs were only in the area of knowledge about astronomy, whereas a student whose spatial reasoning skills were limited, spatial instruction in the form of immersive environments (Resnick, 1994) or microworlds (diSessa, 1988) would be more appropriate. Spatial skills specific to the astronomy domain may be important to provide the ability to apply the knowledge learned.

It may be possible to use of a learner's own inconsistencies as catalyst for model change as well. Since the explanations participants provide show coherence among concepts but may be inconsistent with other aspects of their own knowledge (such as the Elliptical Orbit model and hemispheric differences between the seasons), pointing out such inconsistencies may put the learner in a state of motivation to correct his or her understanding.

Several limitations to this study exist. More participants will allow for several advances, including more stability in the data and a comprehensive examination of the early indicators that an individual may change his or her causal model. Additionally, the stability of the causal models described in this paper over longer periods of time is not empirically well-established.

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