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Evolving Scientific Vocabulary and Language in Middle School Classrooms: Babbling and Gargling on the way to Scientific Understanding

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Abstract

While scientific vocabulary is important, it can often become problematic for students. Sometimes, those words can become a barrier to participation or act as a gatekeeper to success in the science classroom. Under the Next Generation Science Standards, middle school students are expected to model Earth-Moon-Sun motions to explain Moon phases, eclipses, and seasons (NGSS Lead States, 2013). Using a phenomenography lens, we investigated the ways in which students seeing the Moon in nature and related classroom experiences translate into a mental model of lunar phases and how vocabulary is used to communicate these models. Eighth-grade students from three urban middle school classrooms were assessed for spatial ability and understanding of lunar phases. Girls and boys of both high and low spatial ability were interviewed to explore their Moon phase understanding and causal thinking before and after an astronomy unit. One school employed the school district's astronomy curriculum while the other used the REAL Curriculum. Students engaged in babbling (i.e., inarticulate but somewhat correct descriptions) and gargling (i.e., using many technical terms without evidence of understanding) with much greater frequency in pre-interviews. Students who developed correct vocabulary and used it comfortably in interviews were more likely to also display correct Moon phase conceptions. REAL Curriculum's project-based approach to teaching astronomy and related vocabulary through hands-on, contextualized projects and activities (e.g., Moon observation journals) produced greater vocabulary gains.

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Introduction

Under the Next Generation Science Standards (NGSS; NGSS Lead States, 2013), middle school students are expected to model Earth-Moon-Sun motions to explain Moon phases, eclipses, and seasons. Research has identified three common misconceptions about Moon phases (Wilhelm, 2014; Wilhelm, et al., 2022): (1) Something, often clouds, blocks the observer's view of the Moon, making part of it appear dark (Plummer, 2009); (2) Earth or another body's shadow blocks sunlight from the Moon (Baxter, 1989); and (3) part of the Moon's surface is in the Sun's shadow (Trumper, 2001). Misconceptions regarding Moon phase causes are difficult to change but could be linked to improvements in spatial thinking (Mulholland & Ginns, 2008; Wilhelm, 2009; Wilhelm, Cole, Driessen, Ringl, Hightower, Gonzalez-Napoleoni, & Jones, 2022), such as the ability to shift between Earth-based and space-based perspectives (Plummer, Bower, & Liben, 2016) and to identify the terminator line, the demarcation between light and dark (Subramaniam & Padalkar, 2009). Spatial thinking encompasses many mental concepts and the terminology describing these concepts varies among researchers (Wilhelm, 2009). Given that spatial thinking is malleable and can be developed, it has been argued that improving spatial thinking with a curriculum which develops transferrable spatial thinking can increase participation in STEM careers (Uttal, Miller, & Newcombe, 2013). Further, research has suggested that improving students' content-specific vocabulary can help students overcome misconceptions (Seery & Donnelly, 2012; Stemenkovski & Zajkov, 2014).

While scientific vocabulary is important, it can often become problematic for students. Whether technical language in a science classroom or everyday language, we communicate with others on a daily basis. Sometimes, those words can become a barrier to participation or act as a gatekeeper to success. In a science classroom, students encounter words that are unfamiliar because they are only used in science or words that have different meanings in science than in general usage. When English is not a student's first language, it can become an even bigger barrier to success in the science classroom. While teachers want all of their students to learn, they often tend to focus on the correct words when asking questions rather than on the meaning behind what students may be saying. This focus on technical words rather than the meaning behind less articulate answers may act as an inadvertent gatekeeper as well. In this paper we look at the ways in which scientific vocabulary developed differently in two middle school science classrooms. We compare classrooms that used one of two kinds of astronomy unit. Two classrooms used a project-based unit that intentionally incorporates spatially-rich activities to promote the development of spatial thinking along with content understanding. Project-based units are also designed to provide relevant, real-world investigations into phenomena (in this case, the cause of lunar phases) where students learn through benchmark lessons as well as through student-led projects. These both contribute to a positive learning community in the classroom, where discussion of projects and lessons may provide opportunities to learn and apply new scientific vocabulary in more authentic ways than traditional units. This unit aligns with the literature that shows the correlation between spatial thinking and content knowledge (Mulholland & Ginns, 2008; Uttal, Miller, & Newcombe, 2013; Wilhelm, 2009). This same spatial thinking literature also lead us to intentionally sample high and low performing students on a spatial assessment when choosing which students to interview; knowing spatial thinking is correlated with understanding the cause of Moon phases meant that we wanted to sample students who may have different understandings. The other classroom used their usual, district-created unit. This unit includes many of the same topics related to the cause of lunar phases, but the approach is different. Rather than sharing and discussing projects, the lessons are more focused on individual or small group work, often with accompanying worksheets to guide learning. Based on the lesson plans and descriptions provided by the teachers, both units introduced similar scientific terms, though in different ways. Thus, we chose to take a phenomenographic approach to investigate how language may have developed differently in the classrooms by addressing the research questions (1) How does urban middle school students' moon phase language develop over an astronomy unit? and (2) How does the project-based REAL Curriculum compare to a standard urban public school district's unit in impact on middle school students' development of scientific vocabulary during an astronomy unit?

Theoretical Framework

Guided by phenomenography, which is founded on a belief that learning "takes place through an interaction between the student, the content of learning material, and the overall learning environment" (Entwistle, 1997), we seek to uncover the various ways in which students react to the experience of the Moon's phases and positions in the sky and their classroom experiences and how this translates into a mental model of lunar phases. The ontological concern of phenomenography is the relationship between reality and consciousness (Hajar, 2021). In phenomenography, there can be a rational, objective reality, but the human understanding of this reality is constrained by experience, and humans can only describe reality as they have experienced it (Hajar, 2021). Phenomenography is based on the premise that, when investigating people's understanding of phenomena, concepts, and principles, those understandings can be grouped in a limited number of qualitatively different ways (Marton, 1986). Phenomenography can explain how the same phenomenon is experienced in different ways by different people under the same circumstances (Cibangu & Hepworth, 2016). Phenomenographic curriculum research is philosophically grounded in the beliefs that there are differences in the ways people approach learning, that some of these ways are more conducive to effective learning, and that experience and training can change the way in which people approach learning (Micari, Light, Calkins, & Streitwieser, 2007).

We also draw on elements of variation theory, an education-specific subset of phenomenography. Central to variation theory is the notion that people are unlikely to notice and remember an aspect of an experience unless their attention is focused on it (Bussey, Orgill, & Krippen, 2013). Variation theory has identified focal awareness (Eriksson, Eriksson, & Linder, 2020), discernment (Eriksson, 2019), and simultaneity (Ekdahl, Venkat, & Runesson, 2016) as processes underlying noticing. Focal awareness refers to what a person's thoughts focus on during an experience; if a person's awareness is focused intently on a certain aspect of the experience, he or she may overlook other aspects that seem obvious to some people (Bussey, Orgill, & Krippen, 2013; Eriksson, Eriksson, & Linder, 2020). When a person has focal awareness of an aspect and goes one step further, comparing and contrasting that aspect with other natural phenomena, discernment has been achieved (Bussey, Orgill, & Crippen, 2013; Eriksson, 2019). Simultaneity refers to a learner being aware of all critical aspects of a phenomenon and being able to discern them; simultaneity is necessary for the learner to develop true cognitive understanding of a phenomenon (Bussey, Orgill, & Crippen, 2013; Ekdahl, Venkat, & Runesson, 2016). Cognitive load theory indicates that the brain can only be aware of a limited number of aspects simultaneously, so variation theory seeks to guide educators to create experiences which maximize simultaneity among aspects most likely to lead to learning (Bussey, Orgill, & Crippen, 2013).

Variation theory maintains that when students approach an object of learning, there are aspects of the existing and already known, bordered by a space to go beyond these aspects, known as critical aspects (Olteanu, 2018). Students discern the critical aspects by experiencing variations on the object of learning (Olteanu, 2018). Bussey et al. (2013) use the example of people experiencing variations in bananas ranging from green to yellow to brown, allowing them to discern the aspect of ripeness in the banana. An individual's mental model of what a banana is depends on what has been discerned from variations in experience and is unique to that individual (Bussey, Orgill, & Crippen, 2013).

Sense-Making

We also rely on sense-making literature to frame our understanding of how children explain a phenomenon before receiving formal education on it. Sensemaking, closely related to Vygotsky's (1978) theory that people make meaning out of their dialogue with others, is the theory that people retroactively make sense of phenomena they experience by employing mental models, creativity, and curiosity (Rapanta, 2019). When children create self-generated explanations of phenomena, they use intuition based on explanatory primitives (Kapon & diSessa, 2017), calculating an explanation without formal reasoning through shorthand explanations of how the world works created through experience, education, interaction and language (Kapon, 2017). Explanatory primitives, when left unquestioned, give the child a sense of comfort and obviousness, a feeling of understanding the way things are, but with time and experience, the child begins to challenge these intuitive explanations and seek deeper understanding through reason (Kapon & diSessa, 2017).

Babbling and Gargling

We take sensemaking one step further by incorporating the concepts of babbling and gargling in vocabulary development (Mason, 2017; Malara & Navarra, 2017). When making sense of a phenomena encountered before science education on the topic, children lack formal scientific vocabulary with which to describe their experience. Children's dialogue under such circumstances can be rife with babbling. Malara and Navarra (2017), writing in the context of mathematics education, describe algebraic babbling as a process of short sentences and reflection on the meaning of words. Mason (2017) provides an excellent example of algebraic babbling from a discussion with his young son who was pondering the relationship between three plus four and four plus three. In a moment of insight, the boy announced: "anything plus anything is anything plus anything" (Mason, 2017, p. 8). Mason (2017) explains that although the statement is clearly wrong on the surface, it reveals an underlying grasp of the principle that order of addends does not matter which the child could not yet express with formal vocabulary.

In this context, babbling is an analogy for how infants make sense of ambient language by uttering phonetic sounds employed by that language as a precursor to developing vocabulary (Lee, Jhang, Chen, Relyea, & Oller, 2017). Mason (2017) contrasts babbling with gargling, another process of vocabulary development, in which children are aware of vocabulary terms related to a phenomenon but do not understand them, placing incorrect terms in their dialogue, or perhaps using correct terms but only through chance. Like babbling, gargling is not a pejorative term. Research into toddler vocabulary development shows that it is not an all-or-nothing endeavor, but rather a gradual process which includes learning to recognize a word, to speak it, to identify other words commonly occur around it, to find reference points connecting the word to prior knowledge, and to comprehend the word's use in more complex contexts (Fernald, Perfors, & Marchman, 2006; Holyfield, Drager, Light, & Caron, 2017). Likewise, students engaged in gargling are trying the word in their speech, seeking to find its place. Gargling presents a challenge, however, because the researcher needs to evaluate whether a student who uses a term more-or-less correctly has some understanding of the term or merely used it by chance.

The terms babbling and gargling arose out of the discipline of noticing in mathematics education (Scataglini-Belghitar & Mason, 2012) and Vygotsky's (1978) theory of preconceptual and pseudoconceptual understanding (Berger, 2006). During preconceptual thinking, a child thinks abstractly and attempts to group ideas into categories yet lacks the ability to communicate this thinking in a culturally meaningful way to a listener (Berger, 2006). As vocabulary develops, the child moves to pseudoconceptual thinking, in which there are errors in thinking but the child can engage in meaningful discourse with a teacher or other adult (Berger, 2006). Pseudoconceptual thinking is a bridge to conceptual thinking, in which the child acquires a personal meaning which is more or less accurate according to the generally accepted thinking of society (Berger, 2006).

Mental Models and Misconceptions

A mental model is a personal, private representation of how the universe functions, only fully understood and appreciated by the person holding it (Gilbert, Boulter, & Rutherford, 1998). A mental model can be expressed through words or actions, and an expressed model which has been rigorously tested and accepted by the scientific community becomes a consensus model, an accepted scientific model consistent with law and theory (Gilbert, Boulter, & Rutherford, 1998). Science educators want students' mental models to resemble consensus models, but helping students build mental models consistent with laws and theory is no simple task. Students bring a variety of misconceptions to the classroom, and a variety of approaches is often required to cause changes in those models (Pejuan, Bohigas, Jaén, & Periago, 2012). A misconception is not merely an error or incorrect belief, but rather a mental model of how the natural world works which is inconsistent with a normative conception based on scientific law and theory (de Astudillo & Niaz, 1996; Özdemir & Clark, 2007). Misconceptions usually develop before students receive formal education in a subject and are surprisingly resistant to change through instruction (Hewson & Hewson, 1984; Posner, Strike, Hewson, & Gertzog, 1982). Misconceptions tend to rely on intuitive explanations arising from everyday experiences of the world (diSessa, 2019). The process of overcoming misconceptions is one of gradual evolution rather than sudden replacement (Potvin, Sauriol, & Riopel, 2015). While some researchers discuss revolutionary change, which replaces a misconception with a normative conception (diSessa, 2019) and others describe a process of disjointed, context-specific ideas moving toward a cohesive, theory-based or theory-like perspective (Clark, 2006), all agree that the change is slow and challenging (Özdemir & Clark, 2007). It is worth noting that some misconceptions such as the Sun's shadow or the Earth's shadow causing Moon phases have not been found in young children (Wilhelm, 2014), suggesting that children develop some misconceptions during their school years.

The Earth's shadow misconception, essentially a belief that an eclipse caused by the Moon moving behind the Earth causes the Moon to be less than full, is commonly held among students from various cultures and countries (Chastenay, 2016; Saenpuk & Ruangsuwan, 2018; Slater, Morris, & McKinnon, 2018; Türkmen, 2015). Another common misconception is that the Sun casts a shadow into which the Moon frequently travels, causing Moon phases (Trumper, 2001; Türkmen, 2015). Many students also believe that, although the Moon is constantly reflecting sunlight, clouds or some other obstruction in the sky partially obstruct our view of the Moon from Earth, thereby causing Moon phases (Plummer, 2009). This is not an exhaustive list, but these three misconceptions have been frequently uncovered in research involving students and adults (Wilhelm, Cole, Cohen, & Lindell, 2018) One challenge for young learners is that correct modeling of the interactions among the Sun, Earth, and Moon requires spatial abilities such as visualizing the three bodies and mentally rotating them (Plumer, Wasko, & Slagle, 2011).

Spatial thinking encompasses many mental concepts and the terminology describing these concepts varies among researchers (Wilhelm, 2009). It has been suggested that spatial thinking refers to the processes that allow humans to create and manipulate mental representations of the spaces within and between objects in a system, while spatial ability refers to the measurable performance of tasks involving spatial thinking (Cole, Cohen, Wilhelm, & Lindell, 2018). Spatial thinking involves many tasks, including visualizing a system, the ability to relate objects to one's own position, and the ability to rotate objects (Cole, Cohen, Wilhelm, & Lindell, 2018). Newcombe & Frick (2010) summarized the research showing that training in mental rotation not only improves spatial ability but produces generalizable gains which transfer to novel stimuli. Students with high spatial abilities tend to develop a successful model of lunar phases (Wilhelm et al., 2022).

Students' creation of mental models is fundamental to astronomy education (Taylor, Barker, & Jones, 2003). Even in elementary school, students possess mental models of the relationship between the Earth and Sun, but those models can be incorrect, rooted in misconceptions (Dankenbring & Capobianco, 2015). Misconceptions are difficult to change, being deeply rooted in the mental models a student has created of how the universe functions (Cooper & Stowe, 2018). Research has shown, however, that curriculum which has students purposefully connect classroom astronomy lessons with real world observations (such as Moon journals) improves students' mental models of the cause of lunar phases and increases their spatial skills (Cole, Wilhelm, & Yang, 2015).

Project-Based Instruction

The REAL Curriculum, originally developed in 2007, is a project-based instruction (PBI) unit which has been utilized by middle schools in two states with the goal of increasing student understanding of Moon phases and improving spatial thinking (Wilhelm, Wilhelm, & Cole, 2019). PBI is an open-ended, inquiry-based method of teaching that provides rich opportunities for creative thinking to address projects while also learning the content (Wilhelm, Wilhelm, & Cole, 2019). This method of instruction provides ample opportunities for student-centered, contextualized, culturally-relevant science instruction in the classroom (Wilhelm, Wilhelm, & Cole, 2019). The extent, of course, that these features are present in a classroom depends on both the design of the PBI unit and the fidelity with which the teacher implements the unit. While a project is an obvious component of PBI, it is not the only essential feature. First, a driving question (DQ) is necessary to guide the unit (Wilhelm, Wilhelm, & Cole, 2019; Krajcik & Czerniak, 2014). The DQ provides a focus for the content of the unit as well as guidance for the scope of the students' projects. The students also need to create sub-diving questions related to the DQ that they will investigate in their projects. These should be centered on a real-world, relevant phenomenon and framed by the standards. Throughout the unit, teachers will implement benchmark lessons in order to address the standards, be sure students learn what is needed for the unit, and also to address knowledge or practices that students need for their projects. Ideally, experts are also included as project supports or as stakeholders who review and use the results of the student projects. Throughout the unit, teachers should also plan for milestones (Polman, 2000). These are check-in points for the class to learn from and provide feedback on each other's' projects and not just a check-in between students and the teacher. Teachers can and should adapt units and lessons to fit their current students and situation, but need to take care to incorporate the structure of the PBI unit with fidelity in order for their students to reap the benefits of this method of instruction. While there is little literature on how vocabulary develops throughout a STEM-focused project-based unit, one study showed a statistically significant improvement mathematical and science vocabulary in 8th grade students who attended a summer camp utilizing a project-based STEM unit (Bicer, Beodeker, Capraro, & Capraro, 2015).

Materials and Methods

In this study we take a phenomenological approach to address the research questions: (1) How does urban middle school students' moon phase language develop over an astronomy unit? and (2) How does REAL Curriculum compare to a standard urban public school district's unit in impact on middle school students' development of scientific vocabulary during an astronomy unit?

Phenomenography employs a method of research akin to that of a naturalist, in which the focus is on recording what is said and done in a situation with minimal interaction from the researcher (Cibangu & Hepworth, 2016; Hasselgren & Beach, 1997). The most common research tool used in phenomenography is the individual interview (Entwistle, 1997; Stolz, 2020). The researcher should not follow a script or prepare a long list of questions because the goal is to capture the educational experience as naturally as possible (Stolz, 2020) with an emphasis on "the respondent's meaning, rather than on linguistic forms or pre-defined technical concepts" (Entwistle, 1997, p 129). Questions should begin with concrete topics and gradually move to abstract concepts (Entwistle, 1997). Phenomenography can also collect data from artifacts. Drawings can give the researcher a window into the visual aspects of the participant's model Ebenezer & Erickson, 1996; Karatas, Micklos, & Bodner, 2011). Open-ended questionnaires can also be employed (Kersting, Schrocker, & Papantoniou, 2021; Kilinc & Aydin, 2013), as can the analysis of documents created by students during their coursework (Kersting, Schrocker, & Papantoniou, 2021).

We explored students' understanding of Moon phases and their associated spatial thinking in three middle school classrooms (Teacher A, Teacher B, and Teacher C) located in an urban environment in the desert southwest. We interviewed four students from each of three classrooms, two with high spatial ability and two with low spatial ability, one boy and one girl each based on their scores on the Lunar Phases Concept Inventory (LPCI; Lindell & Olsen, 2002) and the Purdue Spatial Visualization Test—Rotations (PSVT-Rot; Bodner & Guay, 1997), which assess lunar spatial thinking and mental rotation ability respectively. The LPCI is a 20 question multiple-choice assessment that addresses both lunar phases content knowledge as well as dimensions of spatial thinking, in a lunar context. The questions on the LPCI can be mapped to the SP, GSV, PP, and CD spatial domains as described by Wilhelm (2009). The PSVT-Rot is a 20 question multiple-choice assessment that addresses mental rotation ability in a general context. The test asks for people to consider a block and that same block after being rotated over one or two axes. Then, the test asks what a different block would look like after undergoing the same transformation. The PVST-Rot was the spatial test chosen for this research as mental rotation ability is crucial to understanding the complex Earth/Moon/Mars system that is constantly in motion. This approach is similar to other research on spatial ability and Moon phases (e.g., Wilhelm, Jackson, Sullivan, & Wilhelm, 2013). We interviewed all students before they began their astronomy unit, and eleven of the twelve students after they completed their unit; one student was unavailable for the post-unit interview. In the pre-unit interview, students were asked questions about the Moon phase and causes. Students were then shown two Moon photographs in the crescent and gibbous phases, asked whether they had seen the Moon look like either or both, and asked to explain what caused the different appearances. Next, students were asked to perform three spatial tasks.

Teacher A and Teacher B used the REAL Curriculum while Teacher C used a district-approved curriculum (see Table 1). Teachers A and B received professional development (PD) on using the REAL Curriculum prior to implementation. They also received classroom supplies necessary for the lessons. The PD lasted more than 25 hours and included modeling of the lessons as well as discussion on how and why they were designed that way. The PD provided opportunities to

Table 1

Curricular Units Used by the Teachers

REAL Curriculum	*District Curriculum*
Can I see the Moon every night and why does it appear to change shape? Students listen to the story, "Many Moons" and discuss the size, distance, and composition of the Moon as a group.	*Ancient Civilizations and the Moon*. Students complete a worksheet to learn how the Earth-Moon-Sun system influences life on Earth. Students research ancient civilizations to understand how those civilizations viewed Moon phases, seasons, and eclipses.
Moon Journals. Students keep daily Moon observation journals for 5 weeks. Students record the position (azimuth and altitude angle) of the Moon, sketch the shape of the Moon, and look for patterns.	*What's Up with the Moon?* Students record observations of the Moon for 30 days. Students identify patterns in their Moon observation calendars. Students develop a model of the Earth-Moon-Sun system to predict lunar phases.
How do I measure the distance between objects in the sky? Students learn to measure the distance between objects in the sky using their fists.	*Earth's Moon Handout*. Students learn vocabulary relating to the Moon and phases such as waxing gibbous, eclipse, and maria.
How can I say where I am on the Earth? Students explore the concepts of latitude and longitude, including where these angles come from.	*Determining Hours of Daylight*. Students use figures of Earth labeled with total hours of daylight by latitude in order to determine hours of daylight for various locations.
How can I locate things in the sky? Students use a sky map to locate stars, planets, and constellations in the sky.	*Origin of the Moon*. Students complete a reading assignment on the various hypotheses about the formation of the Moon and answer questions about the text.
Why do we have seasons? Students model the seasons and discover the cause of seasons.	*The Sun-Earth-Moon System*. Students complete a reading on the composition of the Moon, phases of the Moon, and lunar eclipses, then complete a handout based on their reading.
What can we learn by examining the Moon's surface? Students compare photos of the highlands and the maria to determine the relative age of each, crater density in each.	*Eclipses*. Students develop a model of an esclipse by drawing the expected Sun, Moon, and Earth geometry. Students then use their models to explain why lunar and solar eclipses don't occur every month.
What affects a crater's size? Students brainstorm variables that affect a crater's size and then investigate one of these variables.	*Scale*. Students learn about scale and the relative sizes of the Sun, Moon, and Earth. Students create a final model of the Earth-Moon-Sun system to explain why there are eclipses and why they don't occur each month.
The scaling Earth/Moon/Mars NASA Activity. Students use ratio and proportion concepts to build a scale model (both diameter and distance) of the Earth, Moon, and Mars.	
Moon Finale. Students use foam balls and a light to discover the Earth/Moon/Sun geometries necessary to produce the phases of the Moon. Students refer to their Moon Observation Journals to check whether their geometry matches what was observed in nature.	

*Adapted from (Wilhelm, Wilhelm, & Cole, 2019) both understand the REAL Curriculum as well as to address any content or spatial thinking misconceptions. Teacher C had been teaching in the district and using the district unit for several years prior to data collection. While this unit was new to them, Teachers A and B similarly have taught middle school science for several years prior to data collection. All three teachers have bachelor's degrees in science and master's degrees in science education. Both the district unit and REAL Curriculum introduced vocabulary necessary for explaining the cause of lunar phases. We videotaped two lessons in each teacher's classroom. In the post-unit interview, students were again asked to describe Moon phases and explain their cause. Next, the interviewer asked each question on the LPCI and asked the students to explain the reasoning behind their choices. Interviews were videotaped and later transcribed.

The initial code list included spatial domains (Wilhelm, 2009) and conceptions of Moon phases, with the intention of adding additional codes as they naturally fit. We coded the interviews separately, then compared categories and results, coming to a consensus (Sandelowski, Barroso, & Voils, 2007). While coding, we remained cognizant that students who are learning a new subject often engage in two kinds of discourse: babbling and gargling (Mason, 2017; Scataglini-Belghitar & Mason, 2012). Babbling refers to an attempt to explain one's thinking without knowledge of the technical vocabulary, while gargling is an effort to recite technical terms which one does not understand in the hope the listener interprets them as understanding (Scataglini-Belghitar & Mason, 2012).

Results

Looking at the students in aggregate and by teacher, we saw pre to post increases for all groups (overall, by teacher, by gender within teacher) on the PSVT-Rot, but none of the increases were statistically significant. On the LPCI, all students and all subgroups, except boys in Teacher B's classes, saw significant pre to post gains. We approach this data with some caution as based on the literature, we would expect the PSVT-Rot scores to increase along with the LPCI scores after instruction as spatial thinking is correlated with understanding lunar phases (e.g., Cole, Cohen, Wilhelm, & Lindell, 2018; Wilhelm, Jackson, Sullivan, & Wilhelm, 2013). When looking only at the interviewed students, all but two of them (the low-spatial boy from Teacher C's class and the high-spatial boy from Teacher B's class) improved their post-unit LPCI scores when compared to the pre-unit scores. The PSVT-Rot scores varied across the interviewed students; there was no apparent pattern in how the scores changed pre to post-unit. While we purposefully sampled students by score on spatial ability assessments for interviews, no real patterns emerged post-unit for spatial thinking ability. In post-unit interviews, many students performed worse on the LPCI questions than they did when taking the test in class. For example, the high spatial ability girl from Teacher C's class scored 30% lower on the LPCI questions during the interview than in class. The low spatial ability boy from Teacher C's class scored 20% higher on the LPCI during the interview than in class, but attributed more than half of his correct answers to pure guessing. When we asked students to explain their reasoning, many, like the low spatial boy in this example, said they were just guessing or they provided faulty reasoning.

Moon Phase Causes and Vocabulary Development

Our first research question asks how urban middle school student vocabulary develops during an astronomy unit. In pre-unit interviews, all students demonstrated knowledge that the Moon can appear to take different shapes in the sky, although one boy initially said the Moon only appears as a crescent shape, but later said he had seen the gibbous Moon. Girls demonstrated somewhat greater knowledge of different phases than boys with one girl using the terms wax and wane. The low-spatial-ability boy from Teacher A's class, when asked if he had ever observed the Moon, initially responded no. He later said that he had seen the Moon somewhere in the sky but could not be more specific about its location. The only phases he could describe or draw were crescent and full. The low-spatial-ability girl from Teacher A's class could describe seeing the Moon in various locations across the sky during the day and night and was able to describe more Moon phases.

Students could often demonstrate strong knowledge of the patterns and trends involved in Moon phases while holding misconceptions about their cause. In her pre-unit interview, the high spatial ability student from Teacher C's class was able to describe the gradual changes as the Moon transitions among phases and discussed the Moon's rising and setting yet explained that phases were caused by "the shadow of the Earth…when the Earth is in between" the Sun and Moon.

The high spatial ability girl from Teacher C's class explained how the Moon changes between phases as, "when the Moon orbits around the Earth, the shadows of the Sun kind of, like, change it and you can see different parts of it, which is why there is a light and dark side of the Moon."

The high spatial ability girl from Teacher B's class, in her pre-unit interview, explained the cause of Moon phases by saying "So, Earth is actually slanted, right? So, it's turning, but the Moon is also turning and as it may be behind a cloud or something different in the solar system, and I think that it just kind of makes the shape." Asked about this topic again in the post-unit interview, she first said, "Because there are different shadows from the Sun and from the Moon." Questioned about these shadows, she said, "Well, it's not different shadows, but we just see it as different shadows." Asked for more detail about what she meant by shadow, she replied, "Well, I know it's formed from the reflection, 'cause the sun will reflect onto the Moon and where the Moon is makes the Sun—makes the light look like different shadows, which makes us see the different phases of the

Moon." Although her use of the term shadow was incorrect, she fluently used the terms reflection and phases and had replaced her blocking misconception with a more correct understanding of Moon phases.

The high spatial ability boy from Teacher A's class also struggled with the term shadow in his post-unit interview. Explaining how the appearance of the Moon changes after a full Moon, he said, "we see less, because it's being covered by the shadow and it's turning as it goes orbiting the Moon, and that's why we have two Moon perspectives." Asked about the cause of this shadow, he replied, "Our perspective, and when it's orbiting around, we don't- it starts turning and as it orbits, our perspective is changed, because, we're in front of it, and it can't have all of the light shine on it, because it does not have all of the lights on it, 'cause we are blocking it, and our perspective changes since it orbits." Although this explanation contains some elements of correct understanding, his statement "we are blocking it" seems consistent with the shadow misconception. The low spatial ability boy from Teacher A's class said regarding Moon phases in his post-unit interview that "The Earth's shadow is covering it, maybe." The low spatial ability girl from Teacher A's class also discussed shadows in her post-unit interview, stating "it's like, the shadow of the Moon and then, like, half of the colors, like light, like lightish, and then the others are, like, kind of darkish, where you can see the shadow." When asked the LPCI question on the cause of a new Moon, all three of these students picked an answer involving a shadow.

Curriculum Comparison

Our second research question asks how the REAL Curriculum compares to a public school district's curriculum with respect to vocabulary development. The district curriculum used by Teacher C and the PBI REAL Curriculum used by Teacher B and Teacher A differ significantly in their approach to vocabulary development. The district curriculum has students copy vocabulary terms into their notebooks one day, read articles on other days which use those terms in a manner which sometimes allows contextual inference of meaning, and answer multiple choice questions which require fluency with this vocabulary. For example, students copied the definitions of revolution and rotation into their notebooks, read articles using those terms, and then took a quiz which used the terms in answer choices. The PBI REAL Curriculum introduces the vocabulary and definitions, then immediately has students complete activities where they put the vocabulary into use. For example, after introduction of the terms North Pole, equator, latitude and longitude, students use a globe to locate the poles and equator and then measure latitude and longitude of different cities.

In classroom videos, we observed that Teacher A, although careful to use the term illuminated to describe the half of the Moon receiving sunlight, frequently said shadow to describe the dark half. In contrast, Teacher C only used the term shadow when referring to an actual shadow cast by an object, and Teacher B reminded her students that many believed a shadow caused Moon phases at the start of the unit and asked if that was the cause, leading students to shake their heads. Teacher A's unfortunate use of the term shadow in an incorrect manner likely explains the propensity of her students to do likewise and to struggle with the cause of Moon phases.

Teacher A had a positive vocabulary impact with her frequent use of the term perspective, such as "you did all of this from the perspective of the Earth… Let's go from the perspective of looking down like we're in a spaceship." The high spatial ability boy from her class used the term perspective 23 times in his post-unit interview, such as "our perspective changes since [the Moon] orbits." He never used the term in his pre-unit interview.

Teacher C had students copy the vocabulary terms rotation and revolution into their notebooks but did not use these terms often in instruction. One of the few instances when she used rotation came when she asked students what they observed in a computer simulation of the Earth-Moon-Sun system, and a student answered, "I think the Moon is slowly orbiting around. Very slowly." Teacher C replied, "Well, yeah. Normally. But as the Earth rotates, what does this relate to? How much time is this taking?" Students could be heard saying "a year" and "a day." Teacher C then said, "A day, right? So, this is one day. [inaudible] Alright, so the Moon is also moving, you guys are right." Although Teacher C had students copy the definition of revolution into their notebooks, she only used the words revolution and revolve in the context of this exercise. Her students did not use either vocabulary term in their post-unit interviews. In contrast, the PBI REAL Curriculum directs students to use the terms orbit (which is more precise than revolve) and rotate in their activities. By the end of their unit, seven of the eight students in REAL classrooms were introducing the term orbit into their speech about the Moon and three had brought up the term rotate. One of Teacher C's students introduced the term orbit in both her pre-unit and post-unit interviews.

Teacher A frequently used vocabulary terms while addressing her class and often paused to explain the term's meaning. In her small group lesson employing a lightbulb for the Sun and foam balls for the Earth and Moon, she used the term eclipse several times and directed students to observe a shadow cast on the Moon. Two of her students introduced the term eclipse in their post-unit interviews, using it correctly. She also employed the term perspective several times, and one of her students introduced this term to the post-interview conversation. None of her students used these terms in pre-unit interviews.

Three of Teacher B's students used the term phase fluently in post-unit interviews; none of her students used the term fluently in pre-unit interviews. The terms North Pole, eclipse, reflection/reflecting and New Moon were introduced by two students each who had not used the terms in pre-unit interviews.

Teacher C devoted class time to having students copy vocabulary terms from the board to their notebooks. None of the interviewed students from her class used any of these terms fluently in their post-unit interviews. All three of Teacher C's students who completed post-unit interviews used the term New Moon fluently after not using it in pre-unit interviews. Two of her students also introduced the term phase into the post-unit interview after not using the term in pre-unit interviews. Most of the added vocabulary terms in post-unit interviews from Teacher C's class were terms the students likely employed in an in-class activity which involved partners simulating Moon phases by shining a flashlight on a foam ball representing the Moon.

Two important vocabulary terms with which students continued to struggle after their astronomy units were rotate and revolve. One of Teacher A's students used the term rotate several times in the pre-unit interview. He said that "we start rotating every 24 hours," which initially seems like a correct understanding, but he also said "when the earth rotates, that's how we change seasons" and "if the Moon is rotating over here or whichever way it goes, it rotates around the Sun," both of which suggest that, while he had some familiarity with the term, he did not truly understand it. In the post-unit interview, when asked to explain the new Moon, he said "So, when it's rotating, you don't see it, because it's going around, we can't see it from that perspective." He used the term rotating when he was actually describing the Moon's revolution, which suggests that he did not learn the difference during his astronomy unit, despite some initial familiarity with the term rotate.

One of Teacher B's students, in her post-unit interview, twice used the term rotate to refer to revolution, stating the Moon "rotates around the Earth" and the Earth "rotates around the Sun counterclockwise." She did not use the term rotate in her pre-unit interview, and may have acquired the term with an incorrect definition during the unit. Another of Teacher B's students used the term rotation in an awkward sentence during his pre-unit interview, saying the Moon is "a landform that is part of the earth's orbit and it gives us our night and gives the rotation of having the night and the day." The phrase "gives the rotation" is difficult to parse, but coupled with his earlier mention of the Moon giving us our night, he may have correctly understood that rotation is the correct term for Earth's daily spin on its axis. In his post-unit interview, he said that a "full rotation … would be 24 hours."

Part of Teacher C's instruction included students copying verbatim definitions of rotation and revolution from a slideshow into their notebooks. In the interviews of Teacher C's students, only one used either term, employing the two interchangeably in her post-unit interview, saying "thirty days … is the approximate amount of time it takes [the Moon] to revolve around the Earth," and "it takes approximately 30 days to rotate around the Earth."

Teacher A's students averaged 2.67 vocabulary terms in pre-unit interviews (range: 0-5) and added 4.67 vocabulary terms on average (range: 4-6) after the unit, for 7.34 total vocabulary terms per student. Teacher B's students averaged 6.0 vocabulary terms in pre-unit interviews (range: 4-8) and 5.25 added vocabulary terms after the unit (range: 2-9), for 11.25 vocabulary terms per student. Teacher C's students averaged 2.25 vocabulary terms in pre-unit interviews (range: 1-4) and 3.33 added vocabulary terms after the unit (range: 2-6), for 5.58 vocabulary terms per student. Class B started higher than either of the other classes, but added vocabulary terms at a similar rate to Teacher A on average. While one of Teacher C's students added six terms, on average her students added fewer terms than students from either Teacher A or Teacher B's classes. (See Table 2 and Figure 1).

We observed students overcome misconceptions between pre-unit and post-unit interviews. The high spatial ability girl from Teacher B's class introduced nine new scientific terms in her post-unit interview, the largest gain we saw. In her pre-unit interview, she explained Moon phases by saying the Moon "may be behind a cloud or something different in the solar system, and I think that it just kind of makes the shape." In her post-unit interview she no longer expressed a blocking misconception, instead saying "the Sun will reflect onto the Moon and where the Moon is makes the Sun—makes the light look like different shadows, which makes us see the different phases of the Moon." The high spatial ability boy in Teacher A's class entered the unit believing Moon phases exist because "the Earth sometimes, or a planet sometimes blocks the light of the Moon." He showed a vocabulary gain of six terms, the largest in his class. In his post-unit interview,

Table 2
Vocabulary Terms by Student

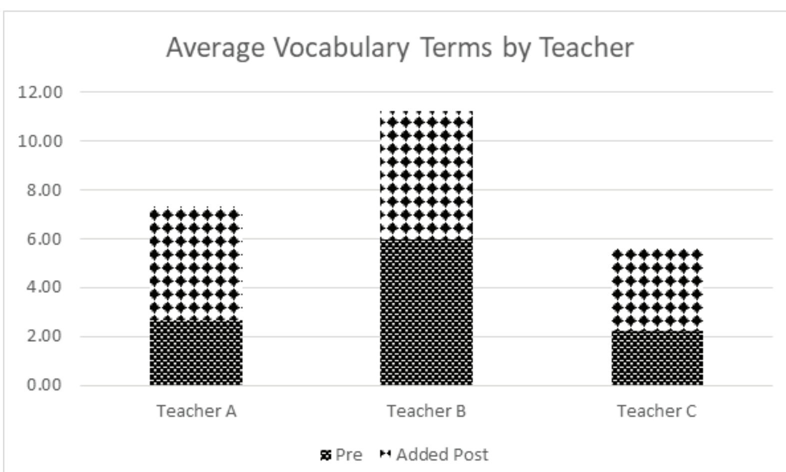
Teacher	*Student*	*Vocabulary Terms in Pre-Unit Interview*	*New Vocabulary Terms in Post-Unit Interview*	*New Terms Used by Multiple Students*
A - REAL	1	0	4	Eclipse, Orbit, New Moon,
	2	5	6	Full Moon, Crescent
	2	5	6	
	3	4	0[a]	
	4	3	4	
B – REAL	5	4	2	Reflection/Reflecting, Phase,
	6	8	5	Eclipse, North Pole, West,
	7	5	9	New Moon, Crescent
	8	7	5	
C – District	9	1	2	New Moon, Phase
	10	1	6	
	11	4	2	

[a] Technical difficulties with the interview video prevented an accurate count. This student was not included in the class average.

he showed conflict between the shadow misconception and a correct conception. For example, on the LPCI question about the cause of a new Moon, he chose both that the Moon is between the Earth and Sun and that the Earth's shadow is covering the Moon. Asked to explain these choices, he said the Moon is "not looking at us anymore, so all of that light is being shined on that side of the Moon where you can't see it...it's not typically blocked by the shadow of the Earth, it's our perspective on Earth." We can see that this student's reasoning shows a correct conception, but his answer choice includes a reliance on his intuitive notion of a shadow.

In Teacher C's class there was less vocabulary development. The high spatial ability girl in her class showed a correct conception in her post-unit interview, which was an improvement over her pre-unit interview in which she initially displayed a shadow misconception but also gave logical reasons for a correct conception. The high spatial ability boy displayed a blocking misconception in his pre-unit interview. In his post-unit interview, he said "the Moon is always half shaded," but when asked why, he responded, "I don't know." He said the appearance of the Moon depends on "the phase we're at in the year." On LPCI questions regarding the cause of Moon phases, he chose inconsistent answers involving both the Moon's position and shadows. The low spatial ability boy offered no explanation for the appearance of the Moon when asked in both interviews. On LPCI questions regarding the cause of Moon phases, he chose shadows. The low spatial ability girl from Teacher C's class was unavailable for the post interview.

Figure 1
Graph of Average Vocabulary Terms Used in Interviews by Teacher



Discussion

In pre-unit interviews, the difference between *seeing* the Moon and *noticing* the Moon was apparent. For example, the student who initially said he had never observed the Moon but later recalled a few positions had seen variations in the Moon's position and phase before, but was not really aware of the Moon and failed to notice its phases and location in enough detail to translate the observations into an understanding of the cause of lunar phases (Mason, 2017). Other students who could describe more variety in the Moon's position showed greater awareness of its phases. These results are consistent with variation theory's concept of focal awareness (Bussey, Orgill, & Crippen, 2013), in that the students who focused awareness on where the Moon appears in the sky were more likely to notice variations in Moon phases.

Misconceptions about the cause of Moon phases were more prevalent than correct understandings in pre-unit interviews, which is not surprising given that students have had many opportunities to explore variations in the Moon's phases and sky position yet have been relying on explanatory primitives (Kapon & diSessa, 2012) to model these phenomena. One interesting episode was a student's use of the phrase "shadows of the Sun." Although this sounds like the Sun's shadow misconception (Wilhelm, 2014), the context suggests the student may not hold this misconception, but rather was engaged in babbling as she struggled to explain that half of the Moon is dark because it faces away from the Sun. This student appears to have been in the process of making meaning from recent observations and an established conception (Smith, Maclin, Grosslight, & Davis, 1997; Yang, Porter, Massey, Merlino, & Desimone, 2020). When first asked why the Moon has different phases, the student answered: "because the shadow of the Earth that it's putting onto the Moon is, like, the Earth is in between." Her later explanation of "a light and dark side of the Moon," after considering the relative positions of Earth, Moon and Sun are likely evidence of a transition to better understanding.

In her post-unit interview, the same student was asked an LPCI question on the cause of a new Moon, she initially chose the answer "The Moon is completely covered by the shadow of the Earth." When asked to explain her reasoning, however, she said, "No, wait. Sorry, it's C. Sorry. I didn't read C. Because the Moon is directly between Earth and the Sun." She went on to explain her reasoning, "Because the Sun would be shining on the other side, but you wouldn't be able to see the bright side of the Moon." This student's initial default to the shadow misconception followed by her rejection of that misconception in favor of the correct scientific explanation when asked for reasoning appears consistent with neurological research showing that even an expert's brain must inhibit certain neurons when faced with a question involving a former misconception (Masson, Potvin, Riopel, & Foisy, 2014; Dunbar, Fugelsang, & Stein, 2007). In this context, the new Moon phase may have been a critical aspect (Olteanu, 2018) for the student, who was able to draw upon what she already knew about the Sun illuminating the Moon's surface and the changing positions of the Sun, the Earth, and the Moon to model a correct explanation for the new Moon phenomenon.

Our interviews show these students engaged in babbling before their astronomy unit and moved to more developed vocabulary to explain their thinking after the unit. Students made statements with incorrect terms in their pre-unit interviews, yet these statements frequently reflected effort to make sense of the causes of Moon phases. For instance, the student who discussed the Earth turning and the Moon turning as the cause of Moon phases seems to have been thinking of Earth's rotation and the Moon's orbit as part of the cause but lacked the formal vocabulary to express this thought. Students with a more developed vocabulary in the post-unit interviews also expressed more advanced models of Moon phases. Students who felt comfortable using the terms perspective and orbit tended to have a correct idea of how those terms explain the cause of Moon phases. Incorrect vocabulary can inhibit correct scientific conceptions, such as when the students who used the term shadow to refer to the non-illuminated half of the Moon believed a shadow or blocking caused Moon phases. Babbling was common in pre-unit interviews, which is not surprising given that most students lacked the scientific vocabulary to explain their thinking about the Moon. Gargling appeared far less often, but gargling can only occur if students know some scientific words related to the topic. In the post-unit interviews, we saw stronger student vocabulary, and babbling and gargling were scarce. Students who developed strong understanding of scientific vocabulary were seen relating that vocabulary to correct scientific conceptions and were more likely to develop correct conceptions. Incorrect vocabulary usage in the classroom could be connected to misconceptions. Students who acquired the habit of using the term shadow to incorrectly refer to a non-illuminated area were more likely to hold shadow and blocking misconceptions.

Vocabulary growth was noticeably stronger among students in classes employing the PBI REAL Curriculum. Teacher C's students, using the district-approved curriculum which employed strategies such as copying vocabulary terms from the board, added terms such as new Moon, full Moon, reflection, perspective, and hemisphere in their post-unit interviews. Teacher A and Teacher B's students, who learned with the REAL Curriculum went further, additionally discussing waxing and waning, the North Pole, the horizon, the equator, orbits, and spheres. Students from Teacher A and Teacher B's classes used more complex vocabulary with greater fluency, suggesting more progress along the continuum from preconceptual thinking through pseudoconceptual thinking to conceptual thinking (Berger, 2006). One explanation for why students in classrooms following the REAL Curriculum showed a greater increase in vocabulary was their use of Moon journals. The Moon journals not only provided opportunities for students to record a drawing of the Moon and note its location, but they also provided an opportunity to write about their Moon observations. Moon journals have previously been shown to increase students' understanding of lunar phases as well as increase their spatial thinking (Cole, Wilhelm, & Yang, 2015). The Moon journals provide a place and a reason for students to use new vocabulary in context and reinforce what was learned in lessons throughout the unit. Teacher C also had students journal about the Moon, but those journals were different in scope. They were focused on creating a calendar that showed the phase each day, but not any additional data or opportunities to write to make sense of their observations. Another explanation could be the projects themselves or the project-based unit design, similar to what Bicer et al. (2015) found in their study. The projects and unit design both allow the students to be able to use their new vocabulary in active, relevant, contextual ways through the lessons, milestones, and the projects. The REAL Curriculum lessons are designed to promote the development of spatial thinking, which has been shown to be correlated with STEM understanding in general (Uttal, Miller, & Newcombe, 2013) and astronomy understanding specifically (Cole, Cohen, Wilhelm, & Lindell, 2018). REAL Curriculum also separated ideas that could cause confusion if combined early in instruction. Teacher C's unit asked students to model (draw) moon phases, eclipses, and seasons all in one diagram. These models were revised throughout the unit three times. We posit that combining these ideas is problematic, partly because they are three complex concepts and partly due to the size of the paper. As scale (i.e., distances between Earth, Moon, Sun) is a critical reason eclipses cannot explain lunar phases (Fanetti, 2001), including both ideas in one diagram on a single sheet of paper makes it difficult to show how the scale affects these phenomena. Then adding seasons into it as well adds to the number of ways students can get confused and struggle with understanding the individual phenomena. In REAL, these concepts were kept clearly separate so that students could learn them individually. While these ideas certainly can be combined, it shouldn't be early in a unit while students are still trying to make sense of the complex ideas.

We saw an increase in vocabulary usage for all teachers, though it was greater with teachers using the REAL Curriculum. Looking at our overall test data (not just the interviewed students), students increased their understanding of lunar phases, but did not show significant growth in their scores on the non-science context spatial assessment (PSVT-Rot). We would expect to see significant increases on both assessments, particular for REAL classrooms as that unit was designed specifically to incorporate spatial experiences to help students develop these crucial skills. The mental rotation (as measured by the PSVT-Rot) is especially important for understanding complex astronomical systems that are constantly in motion, like lunar phases. Then question then is why are students using more vocabulary but still struggling with visualizations? The district unit incorporated a variety of visualizations and modeling similar to REAL. However, the district unit also combined some of these visualizations, potentially impacting those students' ability to develop or practice their spatial visualization and mental rotation as applied to lunar phases. This unexpected result could also simply be reflective of the difficulty of the cause of lunar phases to understand (Baxter, 1989; Wilhelm, Jackson, Sullivan, & Wilhelm, 2013).

Conclusions

A middle school astronomy unit is often the first time students think deeply about the relationships among the Earth, the Sun, and the Moon. This study informs our understanding on what we can do to support students' learning of complex astronomical phenomena such as moon phases by shedding light on which activities seem to help with vocabulary development as well as other aspects of explaining the cause of lunar phases. Teachers should practice listening not just for the vocabulary terms students use, but the meaning they are attempting to convey. Learning science conceptually is difficult enough, but the vocabulary required can make it feel like a foreign language. Vocabulary can be problematic both when students don't know it and when teachers use is inaccurately. Rotate is an excellent example of this. Rotate means to spin on an axis, such as what the Earth does over the course of 24 hours to cause day and night. We often also use it to discuss rotating around another object, such as what the Moon does around the Earth every month or what the Earth does around the Sun over the course of a year, though the better term would be revolve. When teachers use rotate for both situations, it can be confusing. Did they mean rotating on an axis or rotating around another object? This kind of imprecise vocabulary usage can be confusing for students, and gatekeep success in the science classroom, particularly if the teacher is focused on a correct term (possibly gargling terms by students) rather than listening for meaning behind a student's (possibly inarticulate, babbling) response.

We would argue that students should be allowed to babble when learning concepts, and the teacher should pay attention to what they are trying to articulate conceptually, rather than focusing on specific vocabulary terms they are using. By focusing on just the correctness of certain terms, whether used individually or gargled, they may be inadvertently gatekeeping students from success in science classrooms. In all three of these classrooms, we saw teachers embrace the babbling, which was reflected in the test data that showed most student subgroups improving pre to post on their spatial-scientific understandings of lunar phases. We also, unfortunately, saw the effects of imprecise vocabulary usage by teachers impacting students' understanding of those terms.

Using vocabulary terms in an activity shortly after the terms are introduced and defined, helps students understand the terms and incorporate them into their speech about Moon phases and move beyond babbling and gargling. The PBI REAL Curriculum has students purposefully connect their classroom learning to observations outside the classroom through Moon journals and projects, extending vocabulary such as gibbous and waxing to common scenarios outside of school. To paraphrase Eskildsen (2018), teaching vocabulary is not like creating input into a computer, rather it is the more difficult task of coaxing output, with the student owning the vocabulary. Additionally, teacher use of vocabulary in context when modeling an activity helps students develop their vocabulary. Considering the prevalence of the shadow and blocking misconceptions, we urge teachers to be cautious when using the word shadow. If students develop the habit of using the word shadow only when referring to the dark area cast by an object between the observer and light source, they may be more likely to overcome misconceptions involving a shadow. We also advocate for keeping complex, confusing concepts (e.g., lunar phases and eclipses) separate at first. We also suggest incorporating journaling in a meaningful way, where students are able to not just record what they see, but also record positions and write to make sense of what they are observing. By limiting moon journaling to only a drawing of what the moon looks like, students are not prompted to think deeply about what they are seeing and try to make sense of it. We are limited by our Earth-based perspective, so simply observing the moon is not enough. Rather, students need to work to make sense of how what they are seeing is related to what is happening to cause what they see.

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