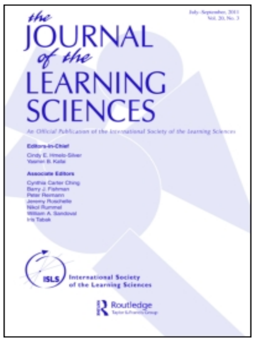

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Making Sense of Space: Distributed Spatial Sensemaking in a Middle School Summer Engineering Camp

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Spatial thinking is important for success in engineering. However, little is known about *how* students learn and apply spatial skills, particularly in kindergarten to Grade 12 engineering learning. The present study investigated the role of spatial thinking in engineering learning at a middle school summer camp. Participants were 26 students (13 female, 13 male), predominantly from underrepresented groups. We took a cognitive ethnographic approach, using observations of hands-on engineering learning activities to identify moments when spatial problems arose and how learners made sense of these problems. We describe these processes as *distributed spatial sensemaking* because they involved both internal (cognitive) processes and also interactions with other learners, materials, and representations. We identified 90 distributed spatial sensemaking episodes in our data set. These episodes facilitated important engineering practices such as hypothesis testing and design iteration. We also found that different activities elicited different types of distributed spatial sensemaking episodes. Our results demonstrate how spatial thinking matters in everyday engineering learning and speaks to the types of engineering learning activities that scaffold particular spatial processes and practices. Our research also shows how cognitive, situated, and distributed theories can be used in tandem to make sense of a complex phenomenon like engineering learning.

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Engineering used to be taught primarily in colleges and universities, but it now plays an important role in formal and informal learning for elementary, middle, and high school students (e.g., Honey & Kanter, 2013; Martinez & Stager, 2013; National Academy of Engineering [NAE] & National Research Council [NRC], 2009; NRC, 2012; National Science Foundation, 2012; Resnick & Rosenbaum, 2013). In fact, engineering activities are an integral part of the Next Generation Science Standards for kindergarten to Grade 12 (K–12) education (NAE & NRC, 2009; NRC, 2012; Next Generation Science Standards Lead States, 2013). Consequently, understanding and enhancing engineering learning in younger students has become a focus of substantial research (NAE & NRC, 2009). We focus here on understanding one important aspect of engineering learning: spatial thinking.

WHAT IS SPATIAL THINKING, AND WHY IS IT IMPORTANT IN ENGINEERING LEARNING?

Carroll (1993) defined *spatial thinking* as the ability to "search the visual field, apprehending the forms, shapes, and positions of objects as visually perceived, forming mental representations of those forms, shapes, and positions, and manipulating such representations 'mentally'" (p. 304). Here we expand this definition to include both internal cognitive processes (e.g., mental rotation of two-dimensional [2D] or three-dimensional [3D] figures) and thinking involving external objects or spatial representations, such as models and diagrams.

A growing body of literature suggests that spatial thinking is important for success in engineering (e.g., Hsi, Linn, & Bell, 1997; Humphreys, Lubinski, & Yao, 1993; Shea, Lubinski, & Benbow, 2001; Wai, Lubinski, & Benbow, 2009). For example, several correlational studies have demonstrated that psychometrically assessed spatial skills strongly predict both performance in college engineering courses (e.g., Hsi et al., 1997; Sorby, 1999, 2009; Sorby & Baartmans, 2000; Sorby, Casey, Veurink, & Dulaney, 2013; Tseng & Yang, 2011) and entry into science, technology, engineering, and math (STEM) professions (e.g., Humphreys et al., 1993; Shea et al., 2001; Wai et al., 2009). These correlations remain strong and significant, even after mathematic and verbal scores are controlled.

Spatial thinking and spatial representations are also nearly ubiquitous in professional engineering practice and engineering learning. Engineers and engineering students must routinely work from maps, models, and diagrams; create spatial representations, such as sketches and models; and tinker with physical or digital objects to solve problems (Dougherty, 2013; Forbus, Usher, Lovett, Lockwood, & Wetzel, 2011; Jang & Schunn, 2012; Johri & Olds, 2011; Kirsh & Maglio, 1994; Martinez & Stager, 2013; Petrich, Wilkinson, & Bevan, 2013; Sorby, 1999; Stevens & Hall, 1998; Tseng & Yang, 2011; Wetzel & Forbus, 2010). Nevertheless, spatial skills are rarely taught, either formally or informally (e.g., NRC, 2006; Uttal, Jant et al., 2013). Consequently, we know relatively little about how to teach spatial skills or when and how they matter in engineering learning, particularly in Grades K–12. Beginning to address these questions is a central focus of this article.

THE ROLE OF SPATIAL THINKING IN ENGINEERING LEARNING: CONSIDERING BOTH COGNITIVE PROCESSES AND CONTEXT

Our research connects two lines of prior work that have been conducted in relative isolation. The first focuses on cognitive spatial processes and individual differences in these processes (e.g., Carroll, 1993; Eliot, 1987; Hegarty, 1992, 2004; Hsi et al., 1997; Linn & Peterson, 1985; Newcombe & Shipley, 2015; Uttal, Meadow et al., 2013). The second emphasizes the situated, distributed, and social nature of spatial thinking and focuses on the role of context-specific resources and practices (e.g., Brown, Collins, & Duguid, 1989; Cole, 1996; Hutchins, 1995a, 1995b; Lave & Wenger, 1991; Rogoff, 2003; Vygotsky, 1978). Here we demonstrate that drawing on both lines of research—considering both cognitive processes and context-specific resources and practices and how they may interact—can help to advance research on the role of spatial thinking in engineering learning. We therefore discuss important contributions from each of these lines of work and their relevance to understanding spatial thinking in engineering learning.

Cognitive Spatial Processes

Our understanding of the cognitive processes involved in spatial thinking comes primarily from cognitive and psychometric approaches to spatial cognition. Research in these traditions has focused either on the cognitive representation and transformation of spatial information or on individual differences in these skills. Hence, this research is primarily conducted in laboratory contexts or uses psychometric tests.

Classifying Cognitive Spatial Processes

Much of the cognitive and psychometric research on spatial thinking has focused on deriving taxonomies of cognitive spatial skills or processes using techniques such as factor analysis, cognitive experiments, and linguistic analysis (e.g., Carroll, 1993; Eliot, 1987; Linn & Peterson, 1985; Newcombe & Shipley, 2015; Uttal, Meadow et al., 2013). Here we draw on a recent taxonomy that is derived from cognitive, psychometric, and linguistic research (Newcombe & Shipley, 2015; Uttal, Meadow et al., 2013) and has shown promise in providing distinctions that are both valid and tractable. This taxonomy classifies cognitive spatial processes along two orthogonal dimensions: intrinsic-extrinsic and static-dynamic. *Intrinsic-extrinsic* refers to whether the spatial information pertains to an individual object or relations among multiple objects or reference frames (Uttal, Meadow et al., 2013). *Static-dynamic* refers to whether the information that is coded involves motion or transformation (Uttal, Meadow et al., 2013). Using these dimensions, it is possible to divide (roughly) spatial processes into four categories: intrinsic-static (e.g., categorizing space), intrinsic-dynamic (e.g., mental rotation), extrinsic-static (e.g., locating an object or self with respect to a frame of reference), and extrinsic-dynamic (e.g., perspective taking).

This taxonomy helps us to identify and discriminate cognitive processes that may be relevant to engineering learning. For example, intrinsic-dynamic spatial processes, such as *mental rotation, spatial visualization, 2D to 3D translation, cross-sectioning*, and *mental simulation*, are particularly predictive of engineering success (e.g., Hegarty, 1992, 2004; Hsi et al., 1997; Sorby, 1999, 2009; Sorby & Baartmans, 2000; Sorby et al., 2013; Tseng & Yang, 2011).

Constraints of a Decontextualized Approach

One potential limitation of using laboratory or psychometric methods to understand spatial thinking is that these methods do not allow insight into how contexts shape thinking and learning (e.g., Brown et al., 1989; Cole, 1996; Hutchins, 1995a, 1995b; Lave & Wenger, 1991; Rogoff, 2003; Vygotsky, 1978). Furthermore, focusing on individual cognitive processes and abilities and using standardized tests to assess these abilities may contribute to deficit models of spatial thinking. For example, girls and children from low socioeconomic status backgrounds tend to score lower on traditional assessments of spatial skills (e.g., Eliot & Fralley, 1976; Levine, Huttenlocher, Taylor, & Langrock, 1999; Levine, Vasilyeva, Lourenco, Newcombe, & Huttenlocher, 2005; Linn & Peterson, 1985; Uttal, Meadow et al., 2013) and are systematically underrepresented in many STEM college majors and careers, in particular engineering (e.g., Chang, 2002; National Science Foundation, 2013). Contrary to the historically dominant notion that spatial skills are innate and inflexible, recent research has demonstrated that these skills are malleable (e.g., Uttal, Meadow et al., 2013). Considering the contexts in which spatial thinking occurs may help us to see more clearly how and when all learners contribute to problem solving rather than focusing only on what some learners lack (Rogoff & Mistry, 1985; Scribner & Cole, 1981; Stevens, 2000; Vossoughi, Escudé, Kong, & Hooper, 2013). It may also lend insight into how these skills are learned and applied and therefore how educators can help learners improve their spatial skills.

Putting Spatial Thinking in Context

To understand the role of context in spatial thinking and engineering learning, we draw on situated (e.g., Brown et al., 1989; Lave & Wenger, 1991), distributed (e.g., Hutchins, 1995a, 1995b), and sociocultural (e.g., Cole, 1996; Rogoff, 2003; Vygotsky,

1978) approaches to understanding thinking and learning. A review of the literature on spatial thinking and learning in context reveals a paradoxical focus. On the one hand, spatial activities are often studied as examples of everyday thinking and learning. Without explicitly focusing on the spatial nature of these activities, researchers have often used spatial activities to study thinking and learning more broadly (e.g., Hutchins, 1995a, 1995b; Lave, Murtaugh, & De La Rocha, 1984; Rose, 2001; Scribner, 1984; Wagner, 1978). On the other hand, very few studies in this tradition have called these activities spatial learning or have connected them to the very large literature from psychology on spatial thinking and learning. Our goal here is to resolve this paradox, explicitly focusing on the spatial learning taking place in one particular set of activities —engineering learning activities—and connecting our in-context observations and analysis to relevant cognitive and psychometric research. We chose engineering learning in particular because spatially and materially based practices, such as collaborating over sketches or models and tinkering with or manipulating objects, are so central to the discipline (e.g., Dogan & Nersessian, 2010; Dym et al., 2005; Jang & Schunn, 2012; Johri & Olds, 2011; Stevens, 2000; Stevens & Hall, 1998).

Considering Social, Material, and Activity Context

Our research examines three specific aspects of learning context. We define the *material context* as the visuospatial representations (e.g., sketches, models, and diagrams) and physical artifacts (e.g., computers, whiteboards, building materials, notes, and prototypes) available to learners in the classroom setting (e.g., Christensen & Schunn, 2007; Forbus et al., 2011; Johri & Olds, 2011; Kirsh & Maglio, 1994; Sorby, 1999; Tseng & Yang, 2011; Wetzel & Forbus, 2010). Visuospatial representations are important tools for individual and collective thinking in both professional engineering practice (e.g., Dogan & Nersessian, 2010; Kirsh, 2010; Stevens & Hall, 1998) and engineering learning (Forbus et al., 2011; Schwartz & Heiser, 2005; Shah, Vargas-Hernandez, Summers, & Kulkarni, 2001; Wetzel & Forbus, 2010). Tinkering with objects is also an important disciplinary practice and learning strategy in engineering (Jant, Haden, Uttal, & Babcock, 2014; Kirsh & Maglio, 1994; Resnick & Rosenbaum, 2013). Finally, thinking with objects and representations has been shown to facilitate cognitive spatial processes (e.g., Frick, Daum, Walser, & Mast, 2009; Frick, Daum, Wilson, & Wilkening, 2009; Funk, Brugger, & Wilkening, 2005; Kirsh, 2010; Zhang, 1997).

Social context is the availability and contribution of other people. Both engineering practice and learning emphasize collaboration (Brereton, Cannon, Mabogunje, & Leifer, 1996; Dogan & Nersessian, 2010; Dym et al., 2005; Shah, Vargas-Hernandez, Summers, & Kulkarni, 2001; Stevens, 2000; Stevens & Hall, 1998). When engineering students or professionals work together to solve a problem, sensemaking is often distributed across a social system (Stevens, 2000; Stevens & Hall, 1998). Each person brings unique knowledge and skills, or repertoires of practice, to the system (Gutíerrez

& Rogoff, 2003; Linn, 2005; Moll, Amanti, & Gonzalez, 1992; Zimmerman, Reeve, & Bell, 2009) and performs specific functions within the system (Hutchins, 1995a, 1995b; Stevens, 2000). Therefore, in order for the distributed cognitive system to function to solve a spatial problem, learners engage in collaborations over shared objects and representations (e.g., Dogan & Nersessian, 2010; Latour, 1990; Radinsky, 2008; Radinsky, Goldman, & Singer, 2008; Shah et al., 2001) and communication of spatial ideas through both talk and gesture (Alibali, 2009; Alibali & Nathan, 2007; Allen, 2003; Beattie & Shovelton, 1999; Ehrlich, Levine, & Goldin-Meadow, 2006; Feyereisen & Havard, 1999; Goldin-Meadow, 1999; Pruden, Levine, & Huttenlocher, 2011; Singer, Radinsky, & Goldman, 2008; Emmorey, Tversky, & Taylor, 2000).

Finally, *activity context* refers to the types of engineering tasks in which learners engage. Many researchers agree that engineering learning activities should be project based (e.g., Brereton et al., 1996; Dym et al., 2005; Ingold, 2000; Kolodner et al., 2003; NRC, 2012; Resnick & Rosenbaum, 2013; Vossoughi et al., 2013). However, there is less agreement about how planned or constrained these activities should be. Some researchers and educators advocate a structured or planful approach (e.g., Brophy, Klein, Portsmore, & Rogers, 2008; Museum of Science, 2015; Project Lead the Way, 2015). In these *engineering design activities*, learners walk through the steps of the engineering design process, working to achieve a specific design goal. Others (e.g., Martinez & Stager, 2013; Resnick & Rosenbaum, 2013; Vossoughi et al., 2013) advocate more open-ended *tinkering activities*, in which learners play and experiment with physical or digital materials. During our observations, we also identified another type of activity, *construction kit activities*, such as Lego Mindstorms, K'nex, or Snap Circuits, in which learners build devices from diagrammatic instructions.

It is reasonable to expect that these social, material, and activity contexts would affect individual cognition. For example, in the current study we hypothesized that different types of activities would elicit different types of spatial thinking. For example, compared to tinkering, engineering design and construction kit activities might elicit more 2D to 3D translation because of the need to build 3D objects from 2D sketches or diagrams. Similarly, both tinkering and engineering design activities might require learners to visualize novel spatial arrangements, whereas construction kits might not.

DISTRIBUTED SPATIAL SENSEMAKING IN ENGINEERING LEARNING

We use the term *distributed spatial sensemaking* to refer to the interaction between cognitive spatial processes and the ways in which these processes are constructed and distributed across context- or activity-specific resources (i.e., materials and people) in a learning context. This idea is based on Gee, Michaels, and O'Connor's (1992) concept of *collective sensemaking*, or "social understandings that are co-constructed between members of a group" (p. 237). We use the term *distributed* instead of *collective* to emphasize the role of both *social* and *material* resources and the potential for the sensemaking work to be divided between different actors (human or nonhuman) in the system (Hutchins, 1995a, 1995b). We add the word *spatial* because in this study we are specifically focusing on how learners make sense of spatial phenomena. Figure 1 illustrates our conception of the interaction between cognitive and contextual factors during an engineering learning activity. Specific activity contexts present specific sensemaking challenges or goals. To achieve these goals, learners draw on internal *cognitive spatial processes*. They also draw on available external (material, social) resources to engage in what we call *spatial sensemaking practices*. For example, we demonstrate that when a group of students is given a specific engineering challenge, they draw on insights contributed by individual learners and distribute problem solving among the different individuals, representations, and materials available. We believe that this approach, which layers on multiple theoretical lenses from the learning sciences in order to improve our understanding of the role of spatial thinking in engineering learning, results in a richer, more authentic, and more complete understanding of this complex learning phenomenon.

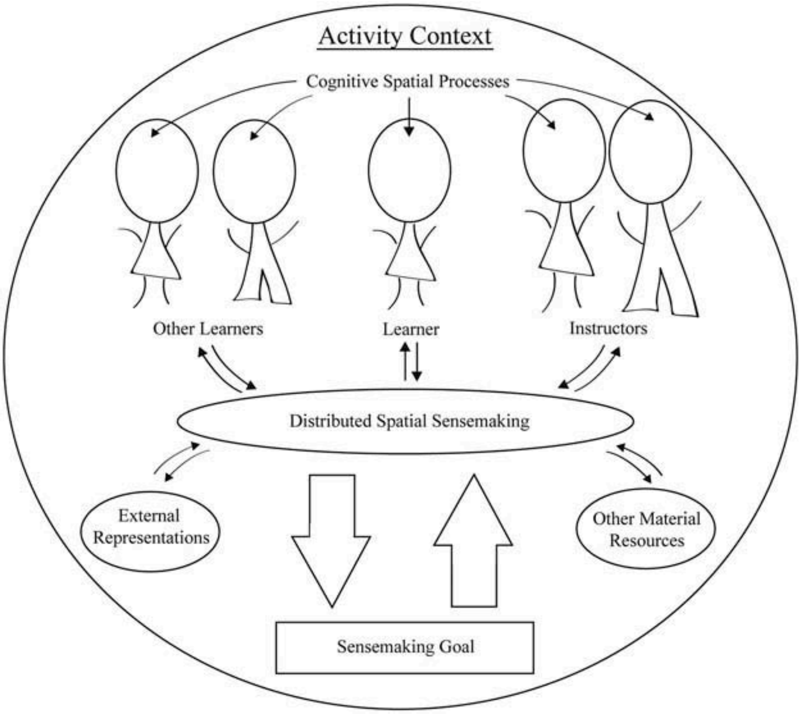

FIGURE 1 The relations between the various elements of distributed spatial sensemaking within a given activity context.

Research Objectives

Using this approach, we examined distributed spatial sensemaking in a middle school summer engineering camp that served primarily urban African American students. There were three goals to this investigation. The first was to better understand the *process* through which spatial thinking might impact engineering learning and performance. The second was to explore ways in which different theoretical lenses from the learning sciences could be coordinated to understand a complex learning phenomenon like engineering learning. Finally, the third was to understand the relative learning affordances of different types of engineering learning activities for fostering STEM-relevant spatial skills. Consequently, our research focused on answering three specific questions:

1. How do learners coordinate cognitive spatial processes and spatial sensemaking practices to make sense of and solve engineering problems?
2. How are these processes and practices dependent on interactions with other individuals and specific artifacts?
3. How might different types of engineering learning activities facilitate different types of cognitive spatial processes and spatial sensemaking practices?

METHOD

Cognitive Ethnography

We conducted a cognitive ethnography (Hollan, Hutchins, & Kirsh, 2000; Hutchins, 1995a) to investigate the interaction between participants' internal cognitive spatial processes and the other people and objects in the environment involved in sensemaking activity. We observed, recorded, and analyzed how middle school students worked through spatial problems during the engineering summer camp and which resources, human or nonhuman, they drew on to do so. This method allowed us to capture not only the meanings constructed by learners but also *how* they were constructed and how their construction was facilitated by both cognitive processes and context.

Research Context

The engineering camp was located in a design studio on an urban university campus in Chicago. It lasted 6 weeks, with each week covering a different engineering topic: aerospace engineering, civil engineering, environmental engineering, electrical engineering, computer programing, and robotics. Camp activities lasted from 9 a.m. to

3 p.m. each day and included a mixture of lecture, hands-on engineering activities (done individually or in small groups), and free choice time. The camp was run by an engineering education organization headed by professional engineers. The organization primarily serves students from groups traditionally underrepresented in STEM disciplines. Instruction was provided by a professional engineer and a college intern, both of whom were African American women. These instructors explicitly emphasized STEM identity development (e.g., Stevens, O'Connor, Garrison, Jocuns, & Amos, 2008) through students' participation in engineering practices like the engineering design process.

We chose this research context for three reasons. First, it provided us with an opportunity to observe groups of learners engaging collaboratively in engineering exploration activities over relatively long periods of time. Given that we are interested in the *process* of engineering learning—and the role that other people and objects might play in this process—time on task and the option to collaborate were important considerations in choosing a research site. Second, the camp covered a range of topics and activities typical of those one might see in other engineering camps or in-school engineering curricula. This was important because it allowed us to explore variation between different types of learning activities and also potentially to generalize some of our findings beyond this one specific context. Third, we chose this camp as our research context because it catered primarily to students from groups underrepresented in STEM. This provided us with an opportunity to tell their engineering learning story. We believe this is important for two reasons. First, it may lead to insights into how to encourage more students from underrepresented groups to pursue careers in engineering and other STEM disciplines. Second, this is a story that is too often neglected in the research literature, where what we know about how people learn is too often only what we know about how people from dominant groups learn.

Participants

Of the 31 learners who participated in all or part of the camp, 26 (13 female, 13 male) learners participated in our research. Participants ranged in age from 9 to 13 and were entering Grades 5 through 8. They self-identified on our demographic survey as Black (n = 19), White (n = 2), Hispanic (n = 2), multiracial (n = 2), and Pacific Islander (n = 1).

Data Collection

We asked all participants to complete a short survey that included questions about demographic information and prior spatial and STEM-related experiences. Then the first author conducted daily observations of camp activities. Using a video camera with two wireless microphones, we recorded all camp activities except for lunch breaks and field trips. The location of the camera changed as classroom activities shifted in type and location, but the camera was always positioned to capture as much of what was going on as possible. The microphones were placed on tables at which learners were working on or discussing projects. Participants knew that the activities were being recorded, but they quickly acclimated to and seemed to ignore the camera and microphones.

Our analyses here concentrate on approximately 50 hr of video from Weeks 2 and 3 of the camp, which focused on civil and environmental engineering. We chose these two weeks because the activities provided the best opportunities to observe learners working collaboratively on a diverse set of engineering learning activities.

Data Coding

Transcription and Segmentation

Videos of classroom interactions were transcribed verbatim, and the transcripts were parsed into turns (Johnstone, 2007). A turn began when a speaker started talking and ended either when another individual started talking or when talk ceased altogether. If the speaker was interrupted, the turn ended, even if the speaker later resumed the same topic. The emphasis in transcription was on accuracy of content and sequence of turns rather than speaker intonation or other discourse properties. Because of our interest in spatial thinking and in interactions with social and material resources in the learning context, we also transcribed visual problem-solving activities, such as gesture and object manipulation.

Identifying Episodes of Distributed Spatial Sensemaking

We next identified episodes of *distributed spatial sensemaking*. We defined these as two or more turns of talk initiated by a learner (a) asking a spatial question, (b) posing a spatial problem statement, or (c) presenting a spatial hypothesis and then focusing on that question, problem, or hypothesis. An episode ended when either the question was resolved or the topic shifted. Distributed spatial sensemaking episodes did not have to include physical objects or representations, but the vast majority did. These episodes were the units of analysis to which all of our other codes were applied.

Multilevel and Multimodal Coding of Distributed Spatial Sensemaking Episodes

To account for both cognitive and contextual factors contributing to sensemaking, we coded each episode at multiple levels and for multiple modalities of thought and communication. Specifically, we coded each episode for learners' sensemaking goal, the cognitive spatial processes and spatial sensemaking practices used to achieve that goal, and the type of activity during which the episode took place.

Sensemaking Goals. In contrast to some of our other categories of codes, which were derived from a combination of inductive and deductive coding (Miles & Huberman, 1994), in coding sensemaking goals we took a bottom-up (inductive) approach, open coding each episode for the type of *sensemaking goal* that was attempted or accomplished in that episode. We identified three categories of goals: interpreting visuospatial representations, interpreting verbal instructions, and exploring/understanding affordances of tools or materials.

Sensemaking Strategies and Resources. The next step was to determine how learners achieved, or attempted to achieve, their sensemaking goals. We coded sensemaking episodes for both the environmental resources (e.g., people, representations, and objects) and the cognitive resources (e.g., cognitive spatial processes) that learners used. In keeping with the tradition of distributed cognition (e.g., Hutchins, 1995a, 1995b; Kirsh, 2010; Kirsh & Maglio, 1994), we coded learners' interactions with other people, representations, and objects—through talk, gesture, and object manipulation—for ways in which these people, representations, or objects facilitated sensemaking or problem solving. In keeping with cognitive psychological theory and methods, we also endeavored to use learners' talk, gesture, and object manipulation as indicators of internal cognitive spatial processes (e.g., Göksun, Goldin-Meadow, Newcombe, & Shipley, 2013; Goldin-Meadow et al., 2012; Ping, Ratliff, Hickey, & Levine, 2011; Pruden et al., 2011; Sauter, Uttal, Alman, Goldin-Meadow, & Levine, 2012; Singer et al., 2008). In conducting this second level of analysis, we drew in particular on prior work in which talk, gesture, object manipulation, or sketching has been used as evidence of mental models of spatial phenomena (e.g., Sauter et al., 2012; Singer et al., 2008; Vosniadou & Brewer, 1992) and on work demonstrating cognitive and developmental links between spatial thinking and spatial talk, gesture, or object manipulation (e.g., Göksun et al., 2013; Levine, Ratliff, Huttenlocher, & Cannon, 2011; Ping et al., 2011; Pruden et al., 2011). Following this dual approach, if a learner used a specific gesture (e.g., moving the hands in a circular motion) to demonstrate the presumed motion of an object, we coded that gesture as evidence of a cognitive spatial process, such as spatial visualization, because it appeared to be an external representation of an internal mental model. We also coded the gesture as a spatial sensemaking practice because it allowed the learner to explicate, discuss, and potentially revise his or her mental model.

Spatial Sensemaking Practices. Using a combination of inductive and deductive coding (Miles & Huberman, 1994) we identified and systematically coded for seven distributed spatial sensemaking practices—strategies for making sense of spatial information that relied on communication with other individuals (learners or instructors) or interactions with external objects and representations. These were (a) *spatial talk*, (b) *hypothesis testing*, (c) *object manipulation* (epistemic, pragmatic, or instructive/explanatory), (d) *gesture* (static, dynamic, or pointing), (e) *working from diagrams*, (f) *analogical or spatial relational comparison*, and (g) *sketching*. Table 1 provides a full list of sensemaking practices with definitions, examples, and references for each.

Cognitive Spatial Processes. We then coded learners' talk, gesture, and object manipulation for evidence of cognitive spatial processes. Again, we used a combination of inductive and deductive coding (Miles & Huberman, 1994), looking first at the types of spatial ideas and processes we observed and then comparing these to categorizations of spatial processes identified in prior cognitive and psychometric literature. For example, if a learner proposed turning a piece to make it fit properly into another piece, we coded for mental rotation (Göksun et al., 2013; Goldin-Meadow et al., 2012; Ping et al., 2011). Similarly, if a learner described or simulated (with gesture or object manipulation) how an earthquake would affect a building, we saw that as evidence of mental simulation. Table 2 provides similar examples for each cognitive spatial skill that we identified.

After making these inferences about the cognitive spatial processes used in sensemaking episodes, we aggregated these processes into categories in order to further our understanding of the types of cognitive spatial processes that are most relevant to engineering learning. We drew on prior work (Newcombe & Shipley, 2015; Uttal, Meadow et al., 2013) that divided these processes into intrinsic-dynamic, intrinsic-static, extrinsic-dynamic, and extrinsic-static spatial processes. For definitions and examples, see Table 2.

Types of Activities. Finally, we examined which types of engineering activities facilitated specific types of spatial processes and practices. To do so, we categorized the camp activities and coded each episode for the type of engineering activity during which it occurred. During the 2 weeks of the camp that we analyzed, learners participated in eight total activities. Based on our observations and insights from prior research, we identified two categories of activities: engineering design activities and construction kit activities. In *engineering design activities*, learners were given a design challenge with specific guidelines and material constraints but were allowed to take multiple creative pathways to a solution. They were encouraged to loosely follow the steps of the engineering design process, explicated by instructors as "Ask, Imagine, Plan, Create, and Improve." In *construction kit activities*, learners were given a kit containing written/diagrammatic instructions and building materials and asked to follow the instructions to build a specific device.[1] Of the eight total activities captured in our data set, we designated

TABLE 1
Categories and Examples of Spatial Sensemaking Practices

Spatial Sensemaking Practice	*Definition*	*Example*	*References*
Spatial talk	Discussing shape, orientation, position or movement of objects, groups of objects, or representations	"Why are you putting this upside down?"	Pruden et al. (2011)
Hypothesis testing	Proposing, modeling, testing, and evaluating an idea or design solution	Learner 1 says, "You really don't need that part." Learner 2 says, "But before, it would slide back." Learner 3 says, "We could tape that and keep it in place."	Kemler (1978), Legare (2012), National Academy of Engineering & National Research Council (2009), National Research Council (2012)
Object manipulation			
Epistemic	Object manipulation for the purpose of easing mental computation	Learner moves the cursor around the screen, trying different tools.	Jant et al. (2014), Kirsh & Maglio (1994)
Pragmatic	Action designed to move one physically closer to a goal	Learner applies hot glue to a tower.	
Instructive/explanatory	Object manipulation for the purpose of explaining something to others	Learner holds two sticks up to the sides of another learner's tower, saying, "You need something on this side and on the other side."	

(*Continued*)

TABLE 1
(*Continued*)

Spatial Sensemaking Practice	*Definition*	*Example*	*References*
Gesture			
Static	Gesture representing a static spatial arrangement	Learner makes V, then X, with hands while saying, "Which one is easier, the V or the X?"	Alibali (2009), Alibali & Nathan (2007), Allen (2003), Beattie & Shovelton (1999), Ehrlich et al. (2006), Emmorey et al. (2000), Feyereisen & Havard (1999), Goldin-Meadow (1999), Goldin-Meadow et al. (2012), Singer et al. (2008)
Dynamic	Gesture representing a dynamic spatial arrangement/process	"For the shaking thing, is it going to collapse *(moves hands apart)* or going to fall down *(moves both hands to one side)*?"	
Pointing	Gesture used to direct attention	Learner points to a diagram.	
Working from diagrams	Referencing diagrammatic instructions to build a device	Learner points to a piece in a diagram. Learner picks up the represented piece and adds it to a structure.	Dogan & Nersessian (2010), Kirsh (2010), Schwartz & Heiser (2005)
Analogical or spatial relational comparison	Comparing one set of spatial properties or relations to another, attending to similarities and/or differences	Learner says, "So arctic is like a Chicago home?" Instructor says, "Mmm-hmm." Learner says, "So, no flat roof."	Christensen & Schunn (2007), Coll et al. (2005), Gentner (1980), Gentner & Markman (1997), Jee et al. (2013), Sagi et al. (2012)
Sketching	Drawing out ideas for the purpose of design	Learner draws a sketch of a climate house.	Anning (1997), Dogan & Nersessian (2010), Enyedy (2005), Forbus et al. (2011), Shah et al. (2001), Wetzel & Forbus (2010)

TABLE 2
Cognitive Spatial Processes Identified in Episodes of Distributed Spatial Sensemaking

Category	*Definition*	*Cognitive Process*	*Example of Verbal Evidence*
Intrinsic-static	"Perceiving objects, paths, or spatial configurations amid distracting background information" (Uttal, Meadow et al., 2013, p. 4)	Disembedding	"Yeah … Do you want to take off this piece right here?"
		Categorizing space	"What's this cone thingy at the top?"
Intrinsic-dynamic	"Piecing together objects into more complex configurations, visualizing and mentally transforming objects, often from 2-D to 3-D, or vice versa. Rotating 2-D or 3-D Objects" (Uttal, Meadow et al., 2013, p. 4)	2D to 3D relation or translation	"There is a way to extrude it to a certain height."
		Cross-sectioning or penetrative thinking	N/A
		Rotation	"Let's turn the angle."
		Sequential thinking or mental simulation	"For the shaking thing, is it going to collapse or going to fall down?"
Extrinsic-static	"Understanding abstract spatial principles, such as horizontal invariance or verticality" (Uttal, Meadow et al., 2013, p. 4)	Spatial relations between objects	"We just had to put this on there and that top on."
		Locating an object or self with respect to a frame of reference	N/A
		Alignment (relating different ways of location coding)	N/A
Extrinsic-dynamic	"Visualizing an environment in its entirety from a different position" (Uttal, Meadow et al., 2013, p. 4)	Perspective taking (updating static representations given self-movement)	"This is actually a good view. Sit right here."
		Updating static representations given movement of objects	N/A

2D, 2-D = two-dimensional; 3D, 3-D = three-dimensional; N/A = not applicable.

three as design activities and five as construction kit activities. Table 3 provides descriptions and categorizations of each of these activities.

Interrater Reliability. For each of our codes for the distributed spatial sensemaking episodes, we also computed interrater reliability scores. To do so, two members of our research team coded 32 of the 90 episodes (the first four episodes of each activity) and compared their scores using Cohen's kappa

TABLE 3
Camp Activities by Type

Activity Type	*Activity Name*	*Activity Description*	*Social Arrangement*
Design activity	Sketchup House	Design a house in Sketchup that is suitable for a particular location and climate of learners' choosing and incorporates a renewable energy source.	Individual activity
	Earthquake Tower	Design a two-story tower using balsawood boards, sticks, and hot glue that will last the longest on an earthquake simulation (shake) table.	Individual activity
	Climate House	Design and build a model house using provided materials (cardboard, plastic bags, tape, hot glue) that will withstand arctic, desert, or tropical climate conditions (separate constraints given for each climate zone).	Part individual, part pair activity
Construction kit activity	Snap Circuits	Construct and test as many of the circuits from the instruction manual as possible.	Individual and pair activity
	Fountain	Build and test a fountain from a Thames & Kosmos Hydropower construction kit with instructions.	Pair or group activity
	Water Wheel	Build and test a water wheel from a Thames & Kosmos Hydropower construction kit with instructions.	Pair or group activity
	Wind Turbine	Build and test a wind turbine from a construction kit with instructions.	Pair or group activity
	Solar Power/Fuel Cell Car	Build and test cars from a construction kit with instructions. Race cars using solar power. Race cars using fuel cell power.	Pair or group activity

calculation (Cohen, 1960). Disagreements were resolved through discussion. Based on Landis and Koch's (1977) guidelines for interpreting kappa statistics, we considered statistics between .61 and .80 indicative of substantial agreement and statistics between .81 and 1.0 indicative of near perfect or perfect agreement.

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[1] We also considered a third category of activity, more open-ended tinkering activities. Although some tinkering occurred within the context of these two more structured types of activities, there were no activities in which the sole purpose of the activity was tinkering.

RESULTS

We first address the question of *how* spatial thinking unfolded and how it mattered for engineering learning in this context by describing the goals of the distributed spatial sensemaking episodes and how they were achieved. This analysis includes an account of both the cognitive spatial processes and spatial sensemaking practices used in each episode. We then discuss our examination of differences in the spatial processes and practices elicited by different engineering activities.

We identified 90 total episodes of distributed spatial sensemaking. Following a mixed-methods approach, we present both qualitative and quantitative analyses of these episodes to demonstrate both how spatial processes and practices were used in context and whether the patterns of sensemaking activity observed in the qualitative analyses were representative of the rest of the data set. The qualitative analyses are based on transcripts of spatial sensemaking episodes that capture both the verbal and gestural aspects of these episodes. In all of these episodes, we refer to learners by pseudonyms that preserve gender. We also refer to the primary and assistant instructors by pseudonyms that preserve both gender and the naming conventions used by learners to address them in this context; we refer to the primary instructor as “Mrs. Barry” and the assistant instructor as “Miss Amanda.”

How Do Spatial Processes and Practices Affect Learning?

In this section, we analyze the ways in which learners used cognitive spatial processes and spatial sensemaking practices in engineering learning. These data suggest that (a) spatial sensemaking played an important role in engineering thinking and learning, (b) spatial sensemaking was distributed or dependent on both cognitive spatial processes and spatial sensemaking practices, and (c) different learners contributed unique repertoires of spatial processes and practices to sensemaking activity.

The Importance of Spatial Sensemaking in Engineering Learning

Episode 1 provides a general demonstration of the importance of spatial sensemaking in engineering learning. In addition to the written transcript of the episode, Figure 2 illustrates the occurrence of visual elements, such as gestures and object manipulations. Miss Amanda and two students, Kristen and Gabrielle, use both cognitive spatial processes and spatial sensemaking practices to arrive at a shared understanding of a dynamic spatial phenomenon. This episode demonstrates how the development of this shared spatial understanding played an important role in the girls’ engineering thinking and learning because it led to design iteration. In the episode, Kristen and

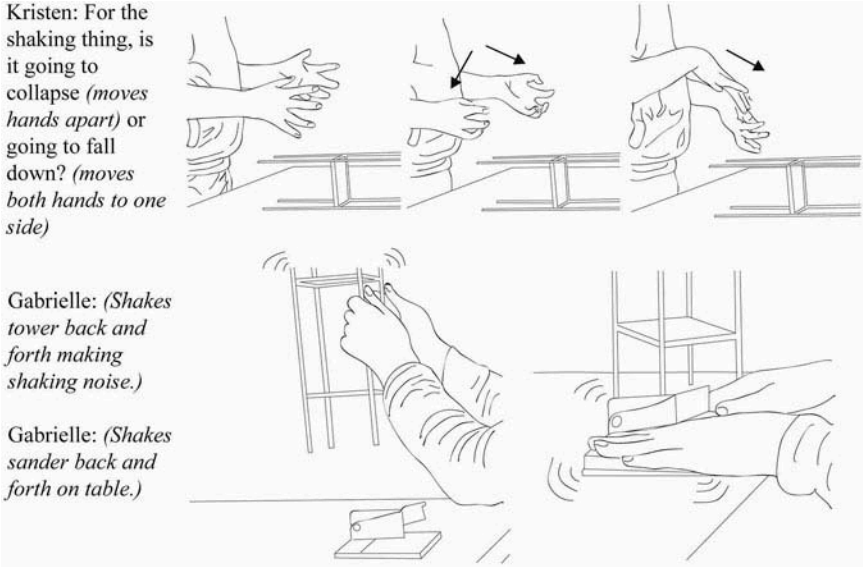


FIGURE 2 Kristen and Gabrielle simulate the motion of their towers on the earthquake simulation table through gesture and object manipulation.

Gabrielle are building "earthquake-proof" towers to be tested on a "shake table," or earthquake simulation table. Kristen initiates a spatial sensemaking discussion with a question about what will happen to the towers on the shake table.

Episode 1

1 Kristen: For the shaking thing, is it going to collapse *(moves hands apart)* or going to fall down *(moves both hands to one side)*?
2 Miss Amanda: It's gonna, it's gonna shake until it breaks.
3 Gabrielle: It's gonna go like *(picks up her tower)*.
4 Kristen: So like break or fall down?
5 Gabrielle: *(Shakes tower back and forth making shaking noise)*
6 Miss Amanda: When I saw these, like, it was just like one or two like cracked. So it, it didn't shatter.
7 Gabrielle: *(Shakes sander back and forth on table)*
8 Miss Amanda: We just gotta listen for a crack.
9 Kristen: I made it stand with one tiny piece!
10 Miss Amanda: Oh, that's nice.
11 Kristen: This is so tall. I don't believe it will last.
12 Kristen: *(Begins adding additional cross-braces to tower)*

In this episode, Kristen and Gabrielle's goal was to understand the constraints of the design challenge. They achieve this goal by using both speech and gesture to describe their mental models of the motion of the shake table and what will happen to their towers on the table. As shown in Figure 2, their descriptions, and in particular their gestures and object manipulations, suggest that they were visualizing, or mentally simulating, the motion of the table (e.g., Gabrielle: *[Shakes sander back and forth on table]*) and the motion of their towers on the table (e.g., Kristen: "For the shaking thing, is it going to collapse *[moves hands apart]* or going to fall down *[moves both hands to one side]*?").

Throughout the episode, this mental simulation of the shake table and tower's motion is distributed among Kristen, Gabrielle, Miss Amanda, and the physical artifacts in their environment, with each component of the distributed cognitive system contributing to the construction of a shared mental model. At the beginning of the episode, Kristen explicates her mental model of the motion of the tower on the table, through spatial talk and gesture, in the form of a question. This proves to be a useful sensemaking strategy, as it prompts Miss Amanda to respond with a verbal description of her own mental model, which apparently differs from Kristen's. Whereas Kristen's initial mental model of the tower has it collapsing or falling down (line 1), Miss Amanda's model has the tower shaking back and forth (line 2) and cracking (lines 6 and 8). As a result of this explicit comparison of mental models, Kristen's mental model begins to change in line 4, where she drops the idea of the tower collapsing in favor of Miss Amanda's word "break." Meanwhile, Gabrielle's object manipulations in lines 3, 5, and 7 can be seen as demonstrations of her own mental model of the motion of the tower on the shake table. They serve the dual purpose of showing Kristen what Gabrielle thinks will happen and inviting feedback from Miss Amanda on whether this mental model is correct. By line 9, Kristen's shifting of the topic suggests that her question has been resolved, and her consequent presentation of a new hypothesis (line 11) and modification to her tower (line 12) suggest that this discussion has caused her to revise her mental model of what will happen to the tower on the table and consequently to devise new ways to enhance the tower's durability.

In other words, by explicating and comparing mental models of the motion of the tower on the table, the learners and their instructor were engaging in a form of hypothesis testing (i.e., Is my mental model right? Does it match your model?) and hypothesis revision (i.e., Can we arrive at a shared model?). Learning to engage in this type of hypothesis testing and revision is fundamental to engineering and other STEM practices. This collaborative hypothesis testing allowed the learners to arrive at a shared understanding of the motion of the tower on the table. This then allowed them to generate and test (through design iteration) new hypotheses about how long particular tower designs would last on the table (e.g., Kristen saying, "This is so tall. I don't believe it will last," and then adding new cross-braces to her tower). These findings demonstrate the important role of socially and materially distributed sensemaking in both advancing learners' understandings of spatial concepts and helping them successfully navigate the engineering design process.

Additional quantitative analyses suggested that the patterns revealed in the qualitative analysis of Episode 1 were representative of patterns seen throughout our data set. For example, in 78 of the 90 sensemaking episodes, sensemaking was distributed among both individuals and objects. There were only 12 episodes in which sensemaking was distributed only among individuals (no objects or representations). Cohen's kappa for the resources used in distributed spatial sensemaking episodes was .84.

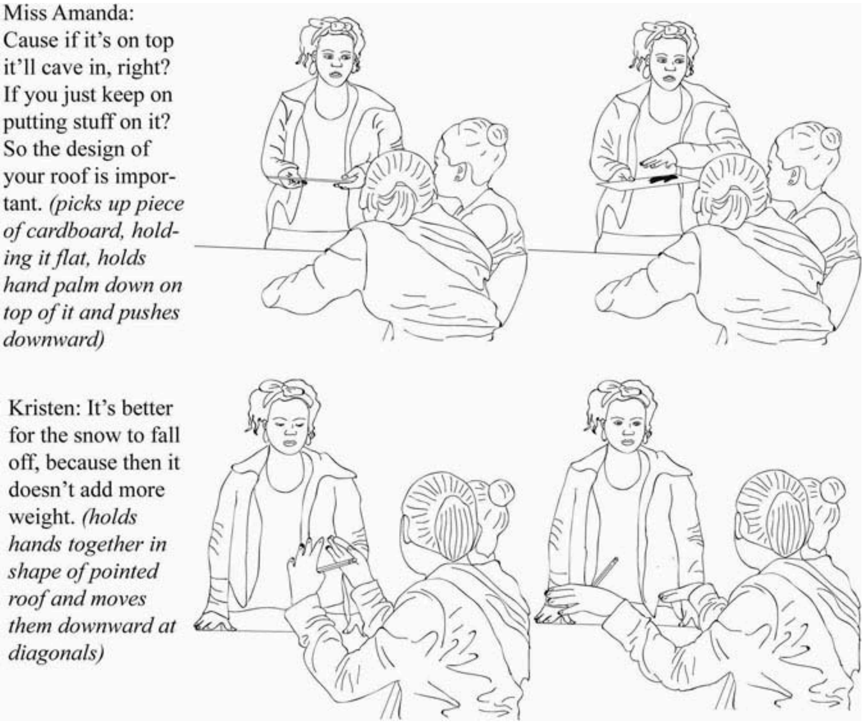
As in Episode 1, distributed spatial sensemaking both required and facilitated engineering thinking and learning throughout our data set. For example, of the 90 episodes, learners initiated 51 by asking a question, 17 by stating a problem, and 22 by offering a hypothesis (κ = .928). All three of these are inquiry practices that are important to engineering thinking and learning. Another important science and engineering practice, hypothesis testing, occurred in the vast majority of episodes (67), and in 51 of these episodes this hypothesis testing led directly to some sort of design modification. In the episodes that did not result in design modification, either the learner decided that his or her design was already correct or ideal or the focus of the sensemaking activity was on understanding why something worked rather than on improving a design or construction.

Finally, Episode 1 provides an example of one of three sensemaking goals that guided episodes of distributed spatial sensemaking. In Episode 1, we saw learners making sense of verbal instructions about a design challenge. This was the primary sensemaking goal of 22 distributed spatial sensemaking episodes (κ = .709). The other two goals that guided sensemaking were interpreting visuospatial representations (33 episodes) and exploring/understanding the affordances of tools or materials (35 episodes). In the sections that follow, we present examples of episodes with these other sensemaking goals and discuss the relation between activity type, sensemaking goals, and spatial processes and practices.

Spatial Sensemaking Is Dependent on Both Cognitive Processes and Sensemaking Practices

In Episode 1, Kristen and Gabrielle demonstrated that spatial sensemaking was important to engineering learning. Episodes 2 and 3 demonstrate how cognitive spatial processes and spatial sensemaking practices interact to facilitate this spatial sensemaking and engineering learning.

In Episodes 2 and 3, Kristen and Gabrielle are working on the Climate House activity. Miss Amanda is helping the girls design roofs for arctic climate houses. Mrs. Barry has told the girls that their houses must withstand 2 pounds of metal discs placed on the roof (representing snow). The



Miss Amanda: Cause if it’s on top it’ll cave in, right? If you just keep on putting stuff on it? So the design of your roof is important. *(picks up piece of cardboard, holding it flat, holds hand palm down on top of it and pushes downward)*

Kristen: It’s better for the snow to fall off, because then it doesn’t add more weight. *(holds hands together in shape of pointed roof and moves them downward at diagonals)*

FIGURE 3 Kristen, Gabrielle, and Miss Amanda use gesture and object manipulation to simulate what might happen to snow on different types of roofs.

girls do not immediately understand the implications of this requirement for the design of their roofs. However, they work through the problem using both cognitive spatial processes and spatial sensemaking practices (see the episode transcripts and Figure 3).

Episode 2

1 Gabrielle: So in the arctic, so arctic is like a Chicago home?
2 Miss Amanda: Mm-hmm.
3 Gabrielle: So, no flat roof.
4 Miss Amanda: No flat roof. That is not going to help.
5 Gabrielle: So it has to be like this *(holds up two pieces of cardboard in shape of pointed roof)*?
6 Miss Amanda: If you think that’s best for …
7 Kristen: It has to be taller.

8 Gabrielle: *(Holds up two pieces of cardboard at a steeper angle)*

Episode 3

1 Kristen: But what if it doesn't cave in, and then they just slide off *(moves one hand downward diagonally)*?
2 Miss Amanda: Well then, if it's steep enough, then it will *(holds hands together in shape of pointed roof and moves them downward at diagonals).*
3 Kristen: So …
4 Miss Amanda: Well it's you guys' design.
5 Gabrielle: This makes no sense.
6 Miss Amanda: What makes no sense?
7 Gabrielle: You say you're going to put it on there, and then it slides off.
8 Miss Amanda: Okay, do you want it to stay on there?
9 Gabrielle: No, but oh, so you want it to slide off? Okay, we want it to slide off.
10 Miss Amanda: Cause if it's on top it'll cave in, right? If you just keep on putting stuff on it? So the design of your roof is important *(picks up piece of cardboard, holding it flat; holds hand, palm down, on top of it and pushes downward).*
11 Kristen: So if it slides off that means the snow slid off?
12 Miss Amanda: Yeah.
13 Kristen: Oh, okay.
14 Gabrielle: So we'd lose the challenge.
15 Miss Amanda: No, why would you lose the challenge?
16 Kristen: It's better for the snow to fall off, because then it doesn't add more weight *(holds hands together, in shape of pointed roof, and moves them downward at diagonals).*

On one level, the participants' talk, gestures, and object manipulation in these two episodes can be seen as windows into their internal cognitive processes. From participants' verbal and gestural descriptions of spatial phenomena, we can infer various types of spatial cognition, such as mental simulation (Episode 3, lines 1, 2, 7, 10, and 16), identification of spatial properties (Episode 2, lines 3, 4, 5, 7, and 8; Episode 3, line 2), and identification of spatial relations (Episode 3, lines 1, 8, 9, 10, 11, and 16). In other words, participants explicate, through talk and gesture, their mental models of both the static spatial properties of the roof (e.g., "flat," "steep," "taller") and the snow's relation to the roof, either static (e.g., "on" the roof) or dynamic (e.g., gesturing or saying "cave in," "slide off," or "fall off" the roof).

These externalizations of internal cognitive processes serve to advance spatial sensemaking by allowing the students to augment their cognitive processes with social and material resources. Just as learners apply cognitive processes to understanding spatial phenomena, they use gesture, talk, object manipulation, spatial analogy, and hypothesis testing as spatial sensemaking practices. As in Episode 1, these practices help them advance their understanding, revise their mental models, and come to a shared understanding by moving some aspects of spatial sensemaking outside of their individual minds and into a distributed, external space. Sensemaking is reliant on material resources, such as hands and pieces of cardboard, as well as social interactions occurring within the triad. For example, Kristen and Gabrielle are both asking questions about the design of the arctic house roofs, and both they and Miss Amanda are contributing resources to try to make sense of the instructions. In fact, throughout Episodes 2 and 3, members of the triad build on and revise one another's ideas by integrating verbal, gestural, and object-based representations. For example, in Episode 2, line 4, Miss Amanda says, "No flat roof. That is not going to help." Then Gabrielle expands on and clarifies this idea, asking, "So it has to be like this?" and holding up two pieces of cardboard in the shape of a pointed roof.

In other words, no one person and no one representational medium is doing all of the sensemaking work; it is distributed between the participants and the available resources.

Spatial analogy is another important spatial sensemaking practice that plays a prominent role in these episodes. For example, Gabrielle draws an analogy between the climates of Chicago and the Arctic and consequently between the spatial properties of Chicago roofs and those of arctic roofs (pointed, not flat). She uses this analogy to infer that the arctic house should not have a flat roof and tries to reconcile this understanding with her understanding of the constraints of the task. Kristen also engages in spatial relational comparison (Jee et al., 2013), or analogical structure mapping (e.g., Gentner & Markman, 1997), to help herself and Gabrielle understand that the weights are analogous to snow and thus should slide off the roof the way that snow slides off a pointed roof (i.e., snow is to real roof as washers are to model roof).

This spatial analogizing is also accompanied and facilitated by both gesture and object manipulation throughout the episodes (see Figure 3). The learners' object manipulations can be seen as both epistemic (helping them work through ideas) and instructive/explanatory (conveying meaning to someone else). In contrast, Miss Amanda's object manipulations are primarily instructive/explanatory. None of these actions are pragmatic object manipulation, as the girls are still planning and not yet constructing their houses. Instead, the girls appear to be planning and visualizing by tinkering with building materials (rather than sketching ideas).

The types of distributed spatial sensemaking practices that we identified in Episodes 2 and 3 occurred systematically across other episodes. For example, in these episodes we observed spatial talk, hypothesis testing, object manipulation (epistemic and instructive/explanatory), gesture (dynamic), and spatial analogy. Of these, spatial talk occurred in all spatial sensemaking episodes. Hypothesis testing occurred in 67 episodes ($\kappa = .748$). Object manipulation occurred in 61 episodes, including epistemic object manipulation (52, $\kappa = .728$), pragmatic object manipulation (40, $\kappa = .937$), and instructive/explanatory object manipulation (27, $\kappa = .742$).

Gesture was used in 32 episodes, including pointing (25, κ = .714), static/iconic (9, κ = .84), and dynamic (8, κ = 1); and spatial relational or analogical comparison was used in 12 episodes (κ = .714). Aside from some of the subtypes of gesture and object manipulation, the only distributed spatial sensemaking practices that we did not observe in Episodes 2 and 3 were working from sketches or diagrams (29 episodes, κ = .75) and sketching (2 episodes, κ = 1).

The types of cognitive spatial processes demonstrated in Episodes 2 and 3 (spatial relations, mental simulation, and spatial properties) were also representative of patterns in sensemaking activity seen throughout our data set. These spatial processes were three of the four most commonly used. Learners reasoned about spatial relations in 80 sensemaking episodes (κ = .714). They engaged in spatial visualization, in the form of sequential thinking or mental simulation, in 30 episodes (κ = .661), and they categorized space in 25 episodes (κ = .709). Other cognitive spatial processes that were not present in Episodes 2 and 3 included rotation (25, κ = .867), perspective taking (6, κ = .784), 2D to 3D translation (4, κ = .636), and disembedding (4, κ = .783).

Different Learners Contribute Unique Repertoires of Processes and Practices to Sensemaking Activity

Further analyses also revealed that individual learners contributed unique repertoires of spatial processes and practices to sensemaking episodes. Because sensemaking was collaborative and distributed, learners both benefitted from and contributed to each other's sensemaking activity. Episodes 4 and 5 illustrate well the contributions of individual learners to distributed spatial sensemaking activity and how groups of students who frequently worked together picked up some of each other's practices.

In both episodes, Jeremy and Carlton are working together on a construction kit activity. In Episode 4, the boys are building a wind turbine while another pair of learners, Jaylen and Brian, is working on the same activity nearby. Jeremy engages in spatial relational comparison using observations about the other group's wind turbine to help himself and Carlton work out problems with their turbine. This is a sensemaking practice that Jeremy repeatedly uses and that repeatedly leads to hypothesis testing and design iteration.

Episode 4

1 Jeremy: *(Pushing gear attached to turbine shaft)* Isn't this supposed to be turning? Did we do something wrong *(walks over to another table where Jaylen and Brian are gluing turbine blades to their functional gear)*?

2 Jaylen: Hold on. I can't see. I'm trying to put these in. *(To Brian)* Just hold steady please. I push it in, and I pull it up.

3 Jeremy: *(To Carlton, back at his own table)* Alright, let's get some glue.

4 Jaylen: *(Losing control of the blade, to Brian)* Push it back in! Oh my God!
5 Jeremy: Well we know that was an epic fail. My question is how did you get yours to turn *(points to Jaylen and Brian's turbine)*? Because ours isn't turning.
6 Carlton: *(Looks at Jaylen and Brian's turbine, removes gear from turbine and flips it over)* Hey look, I fixed it! Wind blows this way *(spins gear with finger)*.
7 Jeremy: Oh, so that's how it does it.

In Episode 4, Jeremy notices that his and Carlton's turbine is not turning properly (i.e., "Isn't this supposed to be turning? Did we do something wrong?"). To figure out what is wrong, Jeremy looks at Jaylen and Brian's turbine and directs Carlton's attention to it. Consequently, Carlton notices that a gear on the other group's turbine is inverted and changes his and Jeremy's turbine to match. Drawing on structure mapping theories of analogy (e.g., Gentner & Markman, 1997: Jee et al., 2013), we can infer that in looking back and forth between and comparing the two wind turbines, the boys are mapping one onto the other, looking for similarities and differences in the spatial configurations of the two wind turbines. In other words, what matches and what does not? When Carlton notices that something does not match (the inverted gear), he concludes that this must be the problem.

In Episode 5, which occurred later in the wind turbine activity, Carlton adopts Jeremy's practice of spatial relational comparison to solve another problem with the wind turbine. This time, Carlton and Jeremy are trying to adjust the angle of their turbine blades to generate the maximum amount of electricity. After some trial and error (lines 1–13), Carlton looks at another group's successful turbine and proposes to Jeremy that they try a blade configuration more similar to that used by the other group (line 14). This process of spatial relational comparison and design modification results in their turbine generating more volts (line 15).

Episode 5

1 Jeremy: I think, if we put a little more tilt on it, it'll go a little bit faster.
2 Mrs. Barry: Yeah, it might do that.
3 Carlton: Alright, you wanna turn off the fan?
4 Jeremy: Now I know how to make a 15 foot [inaudible]
5 Carlton: Let's put some more tilt on it and see what happens *(adjusts turbine blade)*.
6 Jeremy: *(To the turbine)* Why must you hate me!
7 Jeremy: *(Adjusts the turbine blades)* Now let's try.
8 Carlton: Try it now.
9 Mrs. Barry: Make sure you don't hit the edge of the valve unit. If you hit the edge of it, it's not gonna spin.
10 Carlton: I'm not even getting half voltage. The highest is about 140.
11 Jeremy: This one. Adjust a little *(adjusts one of the turbine blades)*.
12 Carlton: Wait lets try it on again. It's this one.

13 Jeremy: Yes!
14 Carlton: We're getting one-forty. We're not getting any more volts. *(To another group)* Wait does yours turn this way? Ours doesn't do that. Wanna see if we can make it turn as easily *(Adjusts turbine blades to match other group's blade angles)*?
15 Carlton: Did we just have nine volts? Ha ha, look at all these volts now.
16 Jeremy: Yeah right. That's, it just says one. This is actually a good view. Sit right here.
17 Carlton: Let me pull up a chair.

Taken together, Episodes 4 and 5 provide an example of the same learner dyad using the same distributed spatial sensemaking practice, spatial relational comparison, across multiple episodes. These episodes also demonstrate how those practices may be initiated by one member of a group (Jeremy) but then picked up and used by another (Carlton). This point can be emphasized by contrasting the strategies used by Jeremy and Carlton in Episodes 4 and 5 with those used by Kristen and Gabrielle in Episodes 1, 2, and 3. In the same way that Jeremy and Carlton repeatedly used spatial relational comparison, Kristen and Gabrielle repeatedly used a combination of gesture, object manipulation, analogy, and mental simulation to make sense of spatial problems.

Repertoires of Practice

The contrast in these episodes also illustrates how different students brought different repertoires of spatial processes and practices to the engineering learning activities and, through collaboration, were able to share them with other students. For example, Jeremy mentioned that his father worked in construction and that prior to participating in the camp he had worked with his dad to make things. Perhaps he learned to use spatial relational comparison from these activities and thus brought this practice to the engineering learning environment, where tasks and materials made these practices similarly advantageous. Likewise, Kristen was the only student who spontaneously (without instructor prompting) used sketching as a way to think through her design during the engineering design activities. She also expressed previous interest and experience in drawing. Thus, sketching was in her repertoire, ready to be used, once she made the connection that it might be useful. In both of these cases, learners applied their own repertories of spatial sensemaking practices to make sense of the activity, simultaneously sharing their practices with others and using them to further group sensemaking.

Which Activities Facilitate Which Types of Spatial Processes and Practices?

We turn now to an analysis of differences between the two types of engineering activities: engineering design and construction kit activities. In focusing on this comparison, we seek to inform the design of engineering learning activities and environments that cultivate a range of spatial skills. We present both examples of episodes from each type of activity and quantitative analyses suggesting patterns of differences between the two types of activities. We demonstrate that distributed spatial sensemaking was important in both of these types of activities, with roughly equal numbers of distributed spatial sensemaking episodes in the construction kit (49 episodes) and design (41 episodes) activities. However, differences in the material constraints and goals of these activities led to differences in learners' sensemaking goals and the cognitive spatial processes and spatial sensemaking practices they used to realize them.

Construction Kit Activities

Episode 6 is from a construction kit activity, the Water Wheel. Jeremy, Jada, and Gabrielle are working together to build a water wheel from diagrammatic instructions. Jeremy begins the episode by presenting a hypothesis regarding where the axle of their water wheel should be inserted into the base structure based on where he sees it in the diagram. This prompts a discussion within the group about where the axle should or could be inserted. This discussion is facilitated both by looking back at the diagram and by manipulating the objects, trying different arrangements.

Episode 6

1 Jeremy: I think this goes like right there *(inserts axle into hole in existing structure)*.
2 Jada: Go at the bottom. It's at the bottom. This in *(grabs water wheel and axle and moves axle into another hole)*.
3 Jeremy: But how is it going to go right there with *(pulls axle out of hole)*...
4 Jada: Let's push this back a little *(attempts to push axle backward through gears on water wheel to make protruding end shorter)* and once we get it in we can take this [inaudible]
5 Jeremy: How about we pull this off *(takes water wheel and axle from Jada and begins trying to take gears off axle, then switches to working axle back through gears without removing them)*?
6 Gabrielle: Look at the [inaudible] *(points to instruction diagram on table)*
7 Jada: Yeah, that's what I'm saying! Don't take everything off! Just push it back a little bit *(points to axle)*!
8 Jeremy: Push what back?
9 Jada: This black thing *(referring to axle)*
10 Gabrielle: *(Picks up instructions and looks at them)*
11 Jeremy: No, it's supposed to come down a little bit. It goes in this hole *(points to place on structure where he wants to insert axle)*.
12 Jada: I know! Push it back a little, so it's going to be able to get it down like that *(grabs axle and gears from Jeremy)*.
13 Jeremy: *(Grabs it back and tries to insert the axle into the hole)*

14 Gabrielle: Wait, wait *(looking at instruction diagrams)*. It's saying … It says hold on to it, like we did on page 6. Hold on to the pinwheel. This is page 38 *(places diagram on table in front of Jada and Jeremy)*.
15 Jada: Come on, wait, wait, wait *(trying to insert axle, turns structure toward herself)*.
16 Jeremy: That's why I said we should push it down a little.
17 Gabrielle: We don't even have page 6! This is page 38.
18 Jeremy: Yeah, right there *(grabs structure from Jada, pushes sides together)*.
19 Gabrielle: Whoa, whoa, whoa.
20 Jada: *(Spins gears and attached water wheel)*.
21 Jeremy: *(Spins gears and attached water wheel)*.
22 Jada: We're done!

Construction Kit Activities Required Making Sense of Diagrams. In this episode, as in other construction kit activities, the learners were trying to understand visuospatial representations and match physical configurations of pieces to the diagrammatic instructions. A chi-square test demonstrated that the construction kit activities elicited more episodes about understanding visuospatial representations (19 episodes, 46%) than the design activities did (3 episodes, 6%), $\chi^2(1, N = 90) = 27.2$, $p < .001$. In contrast, the design activities elicited more episodes about understanding verbal representations of spatial ideas (28, 57%) than the construction kit activities did (5, 12%). Both types of activities elicited sensemaking about the affordances of tools or materials (17 episodes or 41% for design and 18 episodes or 37% for construction kit).

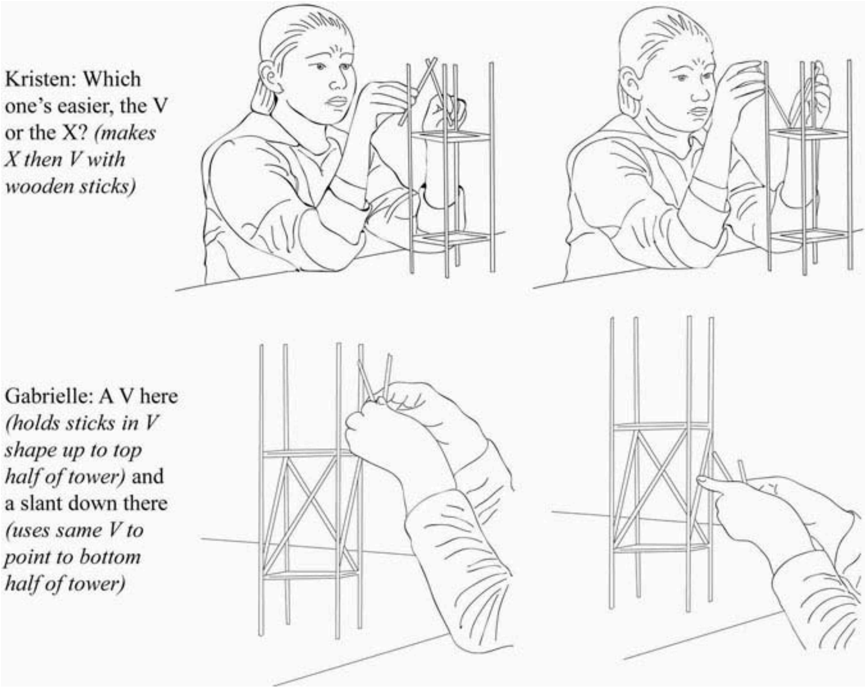
Construction Kit Activities Elicited More Object Manipulation. In Episode 6, we also saw the learners use a combination of epistemic and pragmatic object manipulation to achieve their sensemaking and construction goals. They tried pieces in different configurations and turned the structure, both to better understand how the pieces worked together and to advance the construction of their water wheel. Chi-square tests indicated that epistemic object manipulation occurred more during the construction kit activities than during the design activities (35 episodes, 71.4%, vs. 17 episodes, 41.5%, respectively), as did pragmatic object manipulation (30 episodes, 61.2%, vs. 10 episodes, 24.4%, respectively): epistemic object manipulation, $\chi^2(1, N = 90) = 8.22$, $p < .01$; pragmatic object manipulation, $\chi^2(1, N = 90) = 12.27$, $p < .001$. However, there was no difference between activities in the prevalence of instructive/explanatory object manipulation.

Our analyses suggest that these differences were related to differences in sensemaking goals between the two types of activities. Learners engaged in more pragmatic object manipulation in episodes in which the sensemaking goal was to understand visuospatial representations (21 episodes, 64%) than in episodes in which the sensemaking goal was to understand the affordances of tools or materials (15 episodes, 43%) or in episodes in which the goal was to understand verbal instructions (4 episodes, 18%), $\chi^2(2, N = 90) = 11.1, p < .01$. Correspondingly, episodes during construction kit activities focused more often on understanding visuospatial representations, whereas episodes during design activities focused more often on understanding verbal instructions.

Construction Kit Activities Elicited More Spatial Relations Talk. Finally, in Episode 6, learners talked about spatial relations between objects in order to achieve sensemaking goals, saying things like "This goes at the bottom" or "Push this back a little." A chi-square test showed that spatial relations were considered more during construction kit activities (48 episodes, 98%) than during design activities (32, 78%), $\chi^2(1, N = 90) = 8.96, p < .01$.

Design Activities

The final episode (Episode 7) comes from a design activity, the Earthquake Tower. We selected this episode because it both represents behaviors typical of other episodes



Kristen: Which one's easier, the V or the X? *(makes X then V with wooden sticks)*

Gabrielle: A V here *(holds sticks in V shape up to top half of tower)* and a slant down there *(uses same V to point to bottom half of tower)*

FIGURE 4 Kristen and Gabrielle imagine and communicate possible configurations of cross-braces using gesture and object manipulation.

from design activities and highlights important contrasts between design and construction kit activities. In this episode, Gabrielle, Kristen, Jaylen, and Jason are adding cross-braces to their earthquake towers so that they will be able to withstand the motion of the earthquake simulation table. Kristen initiates the episode, asking a question about how to arrange the balsawood sticks they have all been given to use as cross-braces on their towers. To answer this question, the other learners visually (see Figure 4) and verbally (see transcript) describe their own cross-brace configurations.

Episode 7

1 Kristen: Which one's easier, the V or the X *(makes X then V with wooden sticks)*?
2 Gabrielle: Well, I don't know. I think the V. I don't wanna. He did the V *(points to Jason)*. He did the straight line *(points to Jaylen)*. I did the slant *(points to her own tower)*.
3 Jaylen: I did the straight line.
4 Gabrielle: You did that?
5 Jaylen: That's what I did.
6 Jason: I'm doing a star.
7 Kristen: Ah, okay *(makes upside down V with sticks)*.
8 Jason: The V is actually, I mean the V is really, well actually, maybe not. No.
9 Gabrielle: The slant's the V.
10 Jaylen: I was gonna do a straight line, but I [inaudible].
11 Kristen: Are you just doing a slant? You're not doing anything else *(holds one stick up to tower diagonally)*?
12 Gabrielle: It's gonna be a slant and then a V here.
13 Kristen: Like that *(points to Gabrielle's tower)*?
14 Gabrielle: A V here *(holds sticks in V shape up to top half of tower)* and a slant down there *(uses same V to point to bottom half of tower)*.
15 Kristen: *(Places one diagonal stick on top part of tower and leaves it there)*

Design Activities Required Making Sense of Verbal Instructions. We coded the primary sensemaking goal of this episode as exploring the affordances of tools and materials. However, typical of design activities, the learners are also referencing instructions communicated verbally by the instructor regarding the need for cross-braces on their towers. This contrasts with what we observed in Episode 6 and other episodes from construction kit activities, in which sensemaking was more often focused on interpreting diagrammatic instructions.

Design Activities Elicited More Static/Iconic Gesture. Kristen begins Episode 7 using a hybrid of static/iconic gesture and object manipulation (epistemic and instructive/explanatory) to think through and communicate novel configurations of cross-braces (see Figure 4). She uses her hands and the wooden sticks to create the V and X shapes, both to think through her options for configurations of pieces and also to show her fellow learners what she is thinking. This particular type of gesture, representing static/iconic spatial ideas, occurred more often during design activities (9 episodes, 22%) than during construction kit activities (0 episodes), $\chi^2(1, N = 90) = 11.95$, $p = .001$. However, there was no difference between activities in the prevalence of gestures representing dynamic spatial ideas (5 or 12% in design and 3 or 6% in construction kit) or of pointing gestures (13 or 31% in design and 12 or 24% in construction kit). We can see these differences in the contrast between Episode 7, in which static/iconic gestures play an important role in communication and sensemaking, and Episode 6, in which the only gesture we observe is pointing to diagrams.

Our analyses suggest that the differences in gesture between these two types of activities may have resulted from differences in available material resources. In the construction kit activities, learners worked more from sketches or diagrams (26, 53.1%) than they did during the design activities (3, 7.3%), $\chi^2(1, N = 90) = 21.39$, $p < .001$. Therefore, in the design activities, learners had to imagine and communicate new static spatial configurations through gesture. In contrast, in the construction kit activities, most static spatial arrangements were already represented in diagrammatic instructions and thus did not need to be imagined or physically demonstrated. However, learners would still need to point to those diagrams or to use dynamic gesture to animate the diagrams in order to understand the workings of moving parts.

In addition, differences in sensemaking goals may also have contributed to differences in the types of gestures. For example, learners were more likely to use static/iconic gestures in episodes in which the sensemaking goal was to understand verbal instructions (5 episodes, 23%) or the affordances of tools and materials (4 episodes, 11%) than they were in episodes about understanding visuospatial representations (0 episodes), $\chi^2(1, N = 90) = 7.71$, $p < .05$. Sensemaking episodes about understanding verbal instructions occurred more often in the design activities (in which static/iconic gestures were more frequent), whereas episodes about making sense of visuospatial representations were more prevalent during the construction kit activities (in which static/iconic gestures were less frequent).

Design Activities Elicited More Talk About Categorizing Space. Finally, as Kristen is gesturing the V and X shapes, she is also describing the shapes verbally. We coded this use of V and X both as an example of categorizing space and also as a type of spatial analogy, comparing letter shapes to spatial configurations of pieces. Gabrielle, Jaylen, and Jason also engage in categorizing space by both taking up the descriptive terms *V* and *X* coined by Kristen and adding their own (e.g., "straight line," "slant," and "star") as other possible configurations of pieces. A chi-square test revealed that categorizing space was more prevalent in the design activities (20, 48.8%) than during the construction kit activities (5, 10.2%), $\chi^2(1, N = 90) = 16.56$, $p < .001$. This difference reflects the fact that in the design activities the challenge was to imagine and label new shapes or spatial configurations, whereas in the construction kit activities the challenge was to achieve the correct spatial relations between pieces as already represented or described in diagrammatic instructions.

Other Differences Between Activities

We observed one final interesting difference between construction kit and design activities that is not represented by episodes presented here but that we believe warrants mention. We had initially predicted that both construction kit and design activities would elicit thinking about 2D to 3D translation, as in both activities learners were likely to work from either sketches or diagrams. Although we did find explicit mention of 2D to 3D translation in the design activities (5, 12.2%), we did not find it during the construction kit activities (0), $\chi^2(1, N = 90) = 6.33$, $p < .05$.

Although we were surprised not to find learners visually or verbally working through 2D to 3D translation problems during the construction kit activities, in retrospect our theoretical approach helps explain why this was the case. Learners' application of this particular cognitive spatial skill was affected by both the specific activity context and the nature of the available material resources. For example, the specific diagrammatic instructions provided to learners during the construction kit activities used isometric (3D-perspective) drawings rather than orthographic (true 2D-perspective) projections. This likely made the construction process more an exercise in pattern matching than true 2D to 3D translation. In contrast, the Sketchup House design activity accounted for all but one instance of 2D to 3D translation. In this activity, learners used Sketchup (an open-source 3D computer-aided design platform) to create virtual 3D model homes. Because building things in Sketchup requires making 2D shapes (e.g., squares, circles) and then extruding them into 3D shapes (e.g., cubes, cylinders, cones), this activity's goals and material resources elicited 2D and 3D translation in ways that other activities would not have. Therefore, although we did not expect this difference, examining the material and activity context allowed us to make sense of how and why specific cognitive spatial processes and distributed spatial sensemaking practices were used or not used during each of these activities.

DISCUSSION

Spatial thinking plays an important role in engineering learning above and beyond verbal, mathematical, or scientific reasoning. By observing students in an everyday learning context, we were able to see *how* and *why* spatial thinking mattered for engineering learning and the influences of different activities on spatial processes and practices. We demonstrated, through a mixed-methods approach, that learners integrated both cognitive spatial processes and spatial sensemaking practices to make sense of spatial engineering problems. In addition, we showed that distributed spatial sensemaking helped different learners share their unique repertoires of spatial skills and practices. Finally, we found that different engineering activities elicited different spatial sensemaking goals, spatial sensemaking practices, and cognitive spatial processes. In this section we summarize these findings and discuss their implications for research and practice.

Spatial Sensemaking Includes Cognitive Processes and Context

By looking at spatial thinking in the context of real-world engineering exploration activities, we found that learners' sensemaking was influenced by both internal cognitive processes and interactions with other people, representations, and materials. Learners augmented their cognitive spatial processes with a variety of socially and materially facilitated spatial sensemaking practices. Spatial sensemaking was distributed in (at least) two ways: between spatial representations and objects and between different learners and instructors. The interaction of cognitive spatial processes and spatial sensemaking practices allowed learners to share and revise both mental models of scientific phenomena (e.g., earthquakes, falling snow) and engineering design ideas (e.g., earthquake towers, arctic homes).

Some Processes and Practices Play a Greater Role in Engineering Learning Than Others

We found that some types of cognitive spatial processes and spatial sensemaking practices were used more often than others. Consistent with prior research (e.g., Hegarty, 2004; Hsi et al., 1997; Newcombe, Uttal, & Sauter, 2013; Sorby, 1999, 2009; Sorby & Baartmans, 2000; Sorby et al., 2013; Tseng & Yang, 2011; Wai et al., 2009), we found evidence for intrinsic-dynamic spatial processes, such as mental rotation, mental simulation, and 2D to 3D translation, in learners' talk, gesture, and object manipulation during engineering sensemaking. By looking at sensemaking in context, we also found that intrinsic-static processes, such as disembedding and categorizing space, played an important role in sensemaking, as did extrinsic skills such as identifying spatial relations between objects (extrinsic-static) and perspective taking (extrinsic-dynamic). These important spatial skills might have been missed had we preselected a battery of psychometric assessments or isolated and examined only selected spatial skills or engineering activities in a laboratory setting.

Our approach also shed light on the sensemaking practices learners engaged in to make sense of spatial engineering problems. Our analysis showed that in order to make sense of spatial problems, learners engaged in discussion of spatial ideas augmented by gesture, object manipulation, working from sketches or diagrams, spatial analogy, and hypothesis testing.

One surprise was the relative absence of learners using sketching as a sensemaking strategy. We expected to observe design sketching quite frequently, given prior research on the relation between sketching, spatial thinking, and engineering learning and performance (e.g., Anning, 1997; Dogan & Nersessian, 2010; Enyedy, 2005; Forbus et al., 2011; Shah et al., 2001; Sorby, 1999, 2009; Sorby & Baartmans, 2000; Sorby et al., 2013; Wetzel & Forbus, 2010) as well as instructors' explicit emphasis on sketching during this camp. Instead, although learners occasionally sketched when told to, many avoided it, and only one learner consistently used it as a sensemaking practice. This finding suggests that learners of this age group may need more experience or scaffolding in order to fully incorporate sketching into their spatial sensemaking repertoires.

Spatial Skills as Repertoires of Practice

We have been concerned about the ways in which traditional psychometric assessments of spatial skill are used not only as predictors of engineering success but also as barriers to entry into engineering or other STEM disciplines. Looking at spatial thinking in context has allowed us to see spatial skills and practices more as funds of knowledge or repertoires of ideas or practice (Gutíerrez & Rogoff, 2003; Linn, 2005; Moll et al., 1992; Zimmerman et al., 2009) than as stable individual differences. We saw that all learners engaged in rich spatial and engineering reasoning. Different learners contributed different spatial skills and practices to each engineering learning task (e.g., Kristen and Gabrielle engaging in mental simulation and analogy or Kristen engaging in sketching), and through collaboration they were able to share relevant processes and practices with other learners (e.g., Jeremy sharing his spatial relational comparison strategy with Carlton).

Different Engineering Learning Activities Elicit Different Spatial Processes and Practices

We found that the type of engineering learning activity significantly influenced the types of cognitive processes and spatial sensemaking practices learners used. These differences were likely influenced by differences in the spatial sensemaking goals that learners needed to achieve in different activities as well as by task and material constraints. For example, in the construction kit activities, learners mostly built from diagrammatic instructions. Consequently, there were more spatial sensemaking episodes during the construction kit activities in which the sensemaking goal was making sense of visuospatial representations. Furthermore, because a primary goal during the construction kit activities was to accurately replicate diagrammatic representations, there was more discussion of static spatial relations between objects during these activities. The focus on replicating diagrammatic instructions also explains why both epistemic and pragmatic object manipulation were more prevalent during the construction kit activities than during the design activities. In the design activities, in which the emphasis was on creativity, not accuracy or complexity, learners only had to tinker with objects long enough to understand the challenge and create a functional design. In the construction kit activities, learners had to continue tinkering with materials until they were perfectly configured to match the diagram, or the device would not work.

In the design activities, specific goals and constraints also influenced the processes and practices used in spatial sensemaking. In these activities, the instructor tended to verbally communicate activity goals and constraints. Thus, the most common goal of sensemaking episodes was understanding verbal representations of spatial ideas. Furthermore, in contrast to the construction kit activities—in which the goal was to match spatial configurations represented in diagrams—the design activities elicited the imagination and communication of new spatial configurations. Therefore, during these activities, learners engaged in more categorizing (or describing) space and used more gestures representing static/iconic spatial ideas. In the design activities, static gestures and descriptive spatial categorizations seemed to take the place of the diagrams in communicating relevant static spatial configurations.

Finally, one specific design activity, the Sketchup House, elicited 2D to 3D translation in a way other activities did not. This finding is interesting in light of prior work with college students that demonstrates the importance of spatial visualization skills for successful work in 3D computer-aided design (CAD) environments (Sorby, 1999, 2009; Sorby & Baartmans, 2000; Sorby et al., 2013). It is also interesting that the isometric (3D-perspective) diagrams used in the construction kit activities did not elicit this same type of thinking, particularly in light of research demonstrating that translating between orthographic (true 2D-perspective) and isometric (3D-perspective) projections improves 2D and 3D translation skills in ways that working exclusively in 3D may not (Sorby, 1999, 2009; Sorby & Baartmans, 2000; Sorby et al., 2013).

Implications for Research and Practice

Our findings have theoretical, methodological, and practical implications for researchers and educators. Our research demonstrates the insights that can be gained from integrating theory and methodology from cognitive-psychometric and situated-distributed research. Many researchers have endeavored to describe how individuals use either cognitive processes or social and material resources to engage in spatial thinking and learning. However, few researchers have looked at the interaction between the two, particularly situated within an everyday learning context. Our contextualized approach has allowed us to see how spatial thinking can be facilitated by conversations with people and materials (Resnick & Rosenbaum, 2013; Schön, 1992) and how the social and material conditions of different activity contexts elicit different spatial processes and practices. Taking a contextualized approach has also allowed us to see what cognitive spatial processes identified in the lab or through psychometric assessments might look like in everyday learning contexts and to develop some reliable ways of coding for these cognitive processes using evidence from talk, gesture, or object manipulation.

Our research has implications for the type and structure of activities educators design or use in engineering classrooms and informal learning environments. For example, we found that both construction kits and design activities played important (and complementary) roles in eliciting engineering-relevant spatial skills. We also found that even though the camp activities were not explicitly designed as tinkering activities, many of the sensemaking episodes focused on tinkering goals (e.g., exploring the affordances of tools and materials) and involved tinkering practices (e.g., epistemic object manipulation). These moments of tinkering involved spatial sensemaking practices, elicited cognitive spatial processes, and proved central to learners' completion of both the construction kit and design activities. However, interpreting diagrammatic instructions or design challenge goals and constraints also elicited important spatial processes and practices. Thus, rather than debating whether K–12 engineering curricula should focus on structured engineering design activities, construction kit activities, or open-ended tinkering activities, perhaps we should be developing and promoting curricula that include some of each.

Our findings also emphasize the importance of discussion and collaboration in engineering learning. They advance our understanding of why collaboration matters by demonstrating how it facilitated the transmission of spatial skills and practices from one student to another and provided all students with an external space in which to share and compare mental models and explore spatial ideas through talk, gesture, and other spatial sensemaking practices. These findings also suggest that in collaborative engineering learning environments we should encourage design comparison between students (or groups of students), as this facilitates spatial relational comparison, which in turn facilitates hypothesis testing and design iteration.

Finally, the contrast in 2D to 3D translation between the construction kit activities and the CAD activity is important. This contrast indicates that researchers and educators should further consider and investigate what types of diagrammatic instructions might best facilitate not only construction kit success but also the development of 2D to 3D translation skills in children and adolescents. It also suggests that as CAD programs like Sketchup become increasingly available, further exploration is needed into the role of such programs in developing engineering-related spatial thinking among K–12 learners.

CONCLUSION

We know from prior research that spatial skills are malleable and that differences in spatial skills are the result of differences in cultural and educational experiences. We also know that these skills predict success in engineering. The goal of this study was to better understand how children learn and use spatial skills in engineering exploration activities. We found that by looking at spatial thinking in context—considering both internal cognitive processes and external distributed sensemaking practices—we could provide a more comprehensive picture of how this thinking and learning takes place and how researchers and educators might better facilitate it.

Our research emphasizes the need to examine children's and adolescents' spatial thinking in the context of real-world engineering learning activities, and it demonstrates the insights that can be gained from doing so. We also provide an approach for engaging in such investigations. The prevalence of spatial sensemaking in this camp and the relation we found between spatial sensemaking, hypothesis testing, and design iteration emphasize the importance of considering spatial challenges when designing and delivering engineering instruction. The role that activity context played in eliciting different types of spatial processes and practices indicates that the types of engineering activities in which we engage learners matters for the types of spatial skills and practices they learn. Our approach paves the way for the development of a framework that researchers and educators could use for choosing appropriate activities to develop specific spatial skills and practices. Finally, our approach allowed us to shift away from deficit framing, enabling us to see the unique repertoires of spatial skills and practices each learner brought to the engineering learning activities and the way in which collaborative or distributed engineering learning activities might be used to help learners both develop their own spatial skills and learn new skills from others.

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