In-FUSE-ing STEAM Learning with Spatial Reasoning:

Distributed Spatial Sensemaking in School-based Making Activities

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Abstract

This study examines the role of spatial reasoning in learning among fifth and sixth grade students participating in one set of in-school, technology-enhanced, STEAM (science, technology, engineering, arts, and math) making activities. We focus our analysis on one particular type of reasoning: spatial reasoning. Prior research has shown that spatial reasoning is relevant for problem-solving, participation, and achievement in STEAM disciplines. However, the literature on spatial reasoning lacks qualitative analyses of the processes through which spatial reasoning is learned, enacted, and leads to problem-solving insights, particularly in everyday learning contexts. Spatial reasoning is also underemphasized and undervalued in our schools. And although increasingly-popular, hands-on, making activities have the potential to cultivate spatial skills, spatial reasoning has been largely ignored in the literature on learning through making. Informed by a distributed cognitive perspective and using a combination of qualitative categorical coding and interaction analysis, this study provides a qualitative analysis of the relation between spatial reasoning and learning through making. Our analyses show that during making activities, students engaged in frequent and diverse spatial reasoning with a variety of social and material resources and that the social and material contexts of different making activities facilitated different types of spatial reasoning. Our analyses also show how spatial reasoning developed over time and led to learning.

Keywords: spatial reasoning, making, STEAM learning, qualitative methods, distributed cognition

Educational Impact and Implications Statement

Spatial reasoning skills are implicated in success in STEAM (science, technology, engineering, arts, and math) disciplines but aren't always addressed in text-based curricula. This study suggests that making activities provide a context for late elementary and middle school students to use and develop spatial reasoning skills and to engage in STEAM problem-solving. It also shows how collaboration and work with particular technology tools, such as computer aided design (CAD) software can support the development of particular spatial skills.

Making activities for learning have burgeoned in the last decade. These activities take advantage of technological advances and decreasing costs to provide youth with unprecedented access to tools that resemble those used by STEAM (science, technology, engineering, arts, and math) professionals (e.g., 3D printers, computer aided design (CAD) software, circuit boards, robots, and programming software). They also have the advantage of breaking down disciplinary silos by integrating ideas and practices from different STEAM fields and highlighting shared ideas and practices from these different disciplines (e.g., Peppler, 2013; Sheridan et al., 2014). Many believe these activities can promote learning, interests, and participation in STEAM (e.g., Blikstein, 2013; Hilton, 2010; Martin, 2015; Sheridan et al., 2014; Vossoughi & Bevan, 2014; Vossoughi, Escudé, Kong, & Hooper, 2013). However, we still know relatively little about how students reason with the technology tools used in making activities and what is learned in the process. As these activities gain in popularity and move increasingly from informal contexts into schools, it is essential that we answer these questions.

In this paper, we tackle these questions, focusing on one particular type of reasoning, spatial reasoning. We've chosen to focus on spatial reasoning for three reasons. First, large-scale correlational studies have shown that spatial skills, in the psychometric sense, predict performance in college STEAM courses (e.g., Hsi, Linn, & Bell, 1997; Sorby, 1999; Sorby, 2009; Sorby & Baartmans, 2000; Sorby, Casey, Veurink, & Dulaney, 2013; Tseng & Yang, 2011; Wai, Lubinki, & Benbow, 2009) and participation in STEAM disciplines (e.g., Humphreys, Lubinski, & Yao, 1993; Lubinski, 2010; Shea, Lubinski, & Benbow, 2001; Wai, Lubinki, & Benbow, 2009). Second, qualitative studies of cognition in context have shown spatial reasoning, in the situated and distributed sense, to play a central role in the practices of STEAM professionals (e.g., Dogan & Nersessian, 2010; Stevens & Hall, 1998) and in everyday thinking and learning (e.g., Hutchins, 1995a; Scribner, 1984; Wagner, 1978). Finally, research has demonstrated that spatial reasoning can be improved through training or experience (Uttal et al., 2013). In fact, a recent meta-analysis by Uttal et al. (2013) found a mean effect size of spatial training studies of .47, or almost one half of a standard deviation. The effects of spatial training on performance on transfer tasks (i.e., tasks involving spatial skills other than those trained) were equally promising, with a mean effect size of .48 for transfer to tasks involving different types of spatial reasoning than the ones being trained. Unfortunately, traditional, textbook instruction, of the type often found in K-12 schools, de-emphasizes spatial reasoning, in favor of verbal or analytic approaches to knowledge. As a result, spatial reasoning is systematically undervalued and underdeveloped in our schools (e.g., Ferguson, 1992; NRC, 2006; Newcombe, Uttal, & Sauter, 2013; Schultz, Huebner, Main, & Porhownik, 2003; Sommer, 1978; Wai, Lubinski, & Benbow, 2009).

In contrast, hands-on, project-based, learning activities, like making, have the potential to *spatialize* (Newcombe et al., 2013) STEAM content, because they situate learning within collaborative work with physical and digital objects and spatial representations. Evidence for this comes from both cognitive-developmental and situated-distributed examinations of learning. For example, developmental studies have shown that object manipulation, in the form of puzzle play or manual rotation, improves preschoolers' spatial transformation or mental rotation skills (Levine, Ratliff, Huttenlocher, & Cannon, 2011; Ping, Ratliff, Hickey, & Levine, 2011; Verdine et al., 2014). Others have shown that engaging young children in talk and gesture about space improves spatial skills (Ping et al., 2011; Pruden, Levine, & Huttenlocher, 2011).

Similarly, a situated-distributed account of STEAM thinking and learning by Stevens and Hall (1998) showed that the co-construction of external spatial representations – by both a geometry student working with a tutor and professional engineers designing a roadway – facilitated the collaborative development of spatial understandings that were consequential for math and engineering problem-solving. These authors emphasized the contrast between reasoning in these two contexts and the ways in which math problems are traditionally taught and assessed in schools. Traditional school mathematics privileges analytic approaches (i.e., formulas and calculations) over spatial ones (i.e., graphs, models, and diagrams) and assesses students' skills in ways that deprive them of the very tools (e.g., CAD software, coordinate grids) and collaborative structures (e.g., talking and gesturing through spatial ideas) that might assist them in spatial solutions to math problems. In contrast, making activities are rich in spatial tools, representations, and opportunities to collaborate.

Finally, studies of both K-12 and college engineering students show that working with certain tools used in makerspaces, such as CAD software, is both spatially demanding and can improve spatial visualization skills, especially if opportunities are provided for mapping between CAD models and physical models or sketches (e.g., Basham & Kotrlik, 2008; Onyancha, Derov, & Kinsey, 2009; Shavalier, 2004; Sorby et al., 2013). Despite this evidence suggesting that making activities are contexts in which spatial reasoning should be learned and applied, analysis of the development of spatial reasoning is conspicuously absent from the literature on learning in these activities. The present study addresses this gap in the literature.

Prior Approaches to Studying and Improving Spatial Reasoning in STEM or STEAM

Despite the lack of literature on spatial reasoning in making, there is a growing body of research examining the role of spatial reasoning in STEM disciplines, particularly science and math (we use STEM instead of STEAM here, because these studies don't tend to focus on arts/design). This work provides some insights into when and how spatial reasoning might matter in STEM thinking and learning. However, because of the way spatial reasoning has been defined and measured in much of this previous work, these insights are somewhat limited. For example, Carroll (1993) defined spatial ability 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). This is a cognitive definition that lends itself to focusing on internal, cognitive processes, such as manipulation of mental representations, processing speed, cognitive load, and working memory. Correspondingly, spatial reasoning has generally been studied as a purely cognitive phenomenon, using laboratory experiments and psychometric tests to isolate and measure internal cognitive processes.

Take for example, Shepard and Metzler's (1971) canonical study of mental rotation. These researchers found that when presented with drawings of two- or three-dimensional objects in different orientations, participants took longer to match objects displayed in more disparate positions, with response times corresponding to the angular difference between the two objects. Based on these differences in reaction times, the researchers concluded that to perform the matching task, participants were actually mentally rotating mental representations of the objects. The further the participants had to rotate their mental models, the longer the matching task took.

Similarly, studies of working memory – the short-term memory store involved in holding in mind the information necessary to complete complex tasks (Engle, 2002) – have demonstrated the role of both working memory capacity and interference with working memory processes in performance on spatial reasoning tasks. For example, Ramirez, Gunderson, Levine, and Beilock (2012) found that for girls with high working memory capacity, spatial anxiety negatively interfered with performance on mental rotation problems. Based on work by Beilock and DeCaro (2007) on math anxiety and math problem-solving, they argue that this was because individuals with high working memory tended to rely on problem-solving strategies that demanded working memory. Therefore, when working memory was taxed by anxiety, and therefore was less available for problem-solving, performance suffered more than it did for those with low working memory, who did not rely on such strategies.

Studies such as these have provided valuable insights into the internal cognitive processes involved in spatial reasoning. However, they de-emphasize important aspects of what it means to reason spatially in real-world thinking and learning contexts. For example, we know from situated (e.g., Cole, 1996; Lave, 1998) and distributed (e.g., Hutchins, 1995a; 1995b; Stevens & Hall, 1998) accounts of thinking and learning that external tools, representations, and collaboration play important roles in facilitating reasoning. Although studies in this tradition have tended not to explicitly refer to ‘spatial reasoning’, a close reading of the types of thinking and learning they describe suggests that this is, in many cases, what they are describing. For example, in Hutchins’ (1995a) account of a distributed cognitive system working together to dock the U.S.S. Palau in the San Diego Harbor, Hutchins described the narrow channel, the speed and angle of the boat, the crew’s inability to reverse the propeller to slow down the ship, the need to spin the wheel to adjust the rudder angle, and the disconnect the crew observed between the desired rotation of the rudder and its actual rotation. This is largely an account of spatial reasoning, but not spatial reasoning of the type tested by Shepard and Metzler (1971). In this context, spatial reasoning isn’t defined solely as the manipulation of mental models but rather as the coordination of spatial representations across multiple representational media in a distributed cognitive system.

This difference in definition is consequential for understanding how spatial reasoning is learned and how it might support early STEM or STEAM learning, because it begs the question, 'What are STEAM professionals actually doing when they are engaging in spatial reasoning?' Are they doing things like Shepard and Metzler's mental exercises or are they doing things like the crew of the U.S.S. Palau? Prior research suggests that it's the latter. For example, Stieff (2007) found that although professionals in fields, such as chemistry, are faced with routine diagram or model matching tasks that look like mental rotation tasks (e.g., identifying or matching molecular models or diagrams), when faced with such tasks, they tend to use analytic shortcuts rather than true mental rotation. Further, Stevens and Hall (1998), Stevens (1999), and Dogan and Nersessian (2010) have shown that when faced with more complex, novel spatial problems, experts in fields such as architecture and engineering don't solve these problems just by manipulating mental models, they solve them through the coordinated manipulation of both *internal* and *external* representations (e.g., sketches, models, talk, and gestures). Finally, Kirsh (1995) found that rather than relying solely on working memory, individuals engaged in everyday activities (e.g., cooking, packing, assembling, playing, shopping in the supermarket, and working in a workshop) used space and the spatial arrangement of objects and representations in their environment to reduce the memory demands their tasks. In other words, it is not that internal cognitive processes, such as mental rotation, or capacities, such as working memory, do not play a role in spatial reasoning in the context of STEAM or everyday thinking and learning, but they are only part of the picture.

This is consequential, because it has implications for how we assess and attempt to improve students' spatial reasoning. To date, both the assessments used to measure and the interventions designed to improve spatial reasoning have primarily targeted internal cognitive processes, rather than distributed practices. For example, the correlational studies that have shown spatial skills to be predictive of STEAM achievement (e.g., e.g., Hsi, Linn, & Bell, 1997; Humphreys et al., 1993; Lubinski, 2010; Shea, Lubinski, & Benbow, 2001; Wai, Lubinki, & Benbow, 2009) all measure spatial reasoning using psychometric test items similar to those used by Shepard and Metzler.

In fact, despite a growing body of cognitive, psychometric, and linguistic research, which has attempted to differentiate and categorize cognitive spatial skills (for recent reviews, see Newcombe & Shipley, 2015; Uttal et al., 2013), many of these correlational studies, not only focus solely on cognitive spatial skills but assess only a narrow range of these skills for which there are reliable psychometric tests. For example, a recent taxonomy of spatial skills (Newcombe & Shipley, 2015; Uttal et al., 2013) classified them 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 objects or reference frames (Uttal et al., 2013), while static-dynamic refers to whether the information involves motion or transformation (Uttal et al., 2013). Thus, *intrinsic-static* skills (e.g., disembedding) involve "Perceiving objects, paths, or spatial configurations amid distracting background information" (Uttal et al., 2013, p. 4). *Intrinsic-dynamic* skills (e.g., mental rotation) involve "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 et al., 2013, p. 4). *Extrinsic-static skills* (e.g., locating an object or self with respect to a frame of reference), involve "Understanding abstract spatial principles, such as horizontal invariance or verticality" (Uttal et al., 2013, p. 4), and *extrinsic-dynamic* skills (e.g., perspective-taking) involve "Visualizing an environment in its entirety from a different position" (Uttal et al., 2013,

p. 4). The skills tested by Shepard and Metzler's (1971) tasks and those employed by most of the correlational studies using psychometric assessments, test skills from the intrinsic-dynamic quadrant of this matrix, to the detriment of our understanding of the role that cognitive spatial skills from the other three quadrants play in STEAM thinking and learning.

Similarly, interventions designed to improve spatial reasoning have typically involved spatial training exercises targeting specific cognitive spatial skills, particularly (although not exclusively) skills from the intrinsic-dynamic quadrant (for a recent meta-analysis, see Uttal et al., 2013). These studies have tended to take the form of spatial training in a psychology laboratory, playing video games, or participating in a semester-long or shorter instructional course (Uttal et al., 2013). Although such studies have often given students practice performing mental manipulations based on a particular set of external representations, the focus isn't necessarily on working *with* the representations, but rather on training the cognitive processes that might accompany them. The representations used aren't necessarily the types of representations with which students (or disciplinary professionals) would normally work, but rather stimuli designed specifically for the purpose of improving cognitive spatial skills.

For example, because many engineering undergraduates, particularly females, have been found to struggle with spatial visualization (e.g., Sorby & Gorska; 1998; Sorby 1999), some researchers have experimented with incorporating spatial training exercises into engineering design courses (e.g., Sorby, 1999; Sorby, 2009; Sorby & Baartmans, 2000; Sorby, Casey, Veurink, & Dulaney, 2013). However, rather than have students improve their visualization skills using the types of models they would be likely to work with as professional engineers (i.e., CAD models), this training often involves presenting students with simple geometric figures and asking them to draw the figures from different perspectives using paper and pencil. This approach has proven an efficient way to improve psychometrically-assessed, spatial visualization skills (Sorby & Gorska; 1998; Sorby 1999), but efficient at what cost? From a situated and distributed view of cognition, even if these exercises improve cognitive spatial skills, something is being lost by denying students the opportunity to reason with the actual tools with which they might be expected to reason spatially in professional practice.

In fact, work by Kolvoord, Uttal, and Meadow (2011) suggests exactly what might be getting lost in approaches like this that divorce cognitive spatial processes from the external tools and representations used by disciplinary professionals. This study comes from an area of research aimed not at improving spatial skills, per se, but at improving students' ability to use spatial reasoning to solve disciplinary problems. Many of these types of studies focus on improving students' understanding of specific, narrowly constrained problems from science or math – like identifying and matching molecular diagrams – rather than focusing on how to cultivate the sort of adaptive, resourceful, distributed reasoning practices in which STEAM professionals actually engage. As a result, in some of this work, researchers have presented specific science or math concepts and representations (e.g., topographic maps or number lines) paired with specific gestures, actions, or additional representations, in order to improve students' spatial understandings (e.g., Atit, Weisberg, Newcombe, & Shipley, 2016; Congdon & Levine, 2017). In other work, students have been trained to use specific gestures or actions with specific tools or representations, in order to understand concepts, such as measurement (Novack, Congdon, Hermani-Lopez, & Goldin-Meadow, 2014) or molecular structure (e.g., Stull & Hegarty, 2016).

In contrast, Kolvoord, Uttal, and Meadow (2011) gave students experience working with a tool used by STEM professionals – GIS (geographic information system) software. Instead of instructing students on how to solve one specific problem or type of problem using one specific strategy, students participating in the "Geospatial Semester" explored, learned, and applied GIS software to solve a wide range of problems. At posttest, rather than assessing students' understandings of a particular concept or problem, researchers presented them with novel problems, which could be solved using either spatial (GIS-based) or non-spatial strategies. For example, students were asked to imagine they were a politician planning an election campaign and devise a strategy to get the requisite votes. The researchers found that students in the Geospatial Semester were more likely to propose spatial solutions than their counterparts enrolled in other STEM courses. For example, a student who had taken the Geospatial Semester proposed looking at a demographic map of a district and identifying geographic areas to target with particular sorts of canvassing, while one who had not taken the class proposed talking to constituents to find out about issues that mattered to them. Both are potentially effective strategies, but the first is spatial while the second is not. Students who had taken the Geospatial Semester were also more likely to use spatial language and gestures to describe their solutions, without being specifically trained to do so.

We believe that the ways in which making activities are likely to support spatial reasoning and STEAM learning would more closely resemble the tool-based thinking and learning designed for and documented by Kolvoord, Uttal, and Meadow (2011). This is because, rather than relying upon didactic instructional approaches, making activities tend to be student- and inquiry-driven. Further, although they often span a wide variety of problems and concepts, they are typically centered around particular tools or materials. Finally, the learning outcome of interest in making activities is typically not the understanding of a particular STEAM concept or problem but the development of adaptive problem-solving skills.

Therefore, we take as a guideline here Kolvoord, Uttal, and Meadow's (2011) demonstration of the importance of student-driven work with particular tools in facilitating the development of adaptive spatial problem-solving skills. However, we diverge somewhat from their methods for analyzing spatial reasoning, as these methods are more focused on demonstrating *that* spatial reasoning improved than on showing *how* that happened. This is a limitation shared both by quasi-experimental classroom studies and largescale correlational studies using psychometric tests. These studies tell us *that* spatial reasoning matters for STEAM achievement and participation, but they don't tell us *how* it matters.

One way that researchers have tried to address the 'how question' is through experimental studies. These studies provide some insight into how people engage in spatial reasoning. However, the need for strict control, paired with a cognitive (rather than situated and distributed) framing on spatial reasoning, means that these studies remove important aspects of context that matter for learning.

Providing a Missing Qualitative Account of Spatial Reasoning in Context

In order to fill this gap in prior literature, here, we advocate for studying spatial reasoning in an environment where students are given a wide range of relevant tools and people to think with – a classroom makerspace. We also draw on work by Stevens and Hall (e.g., Hall & Stevens, 2015; Stevens, 1999; Stevens, 2010; Stevens & Hall, 1998) in examining *qualitatively* whether and how spatial reasoning is used, learned, and supports other types of learning in making activities. We argue that a qualitative account of spatial reasoning in the context of real-world making activities is needed to supplement insights garnered from laboratory experiments, quasi-experimental and randomized control trial classroom studies, and correlational studies. In contrast to prior approaches, this approach to examining spatial reasoning will allow us to see *how* reasoning unfolds in context, *how* it is supported by particular tools, representations, and collaborations, and *how* it leads to STEAM problem-solving insights and learning.

To frame this investigation, we draw on distributed theories of thinking and learning (e.g., Goodwin, 2000; Hutchins, 1995a; 1995b; Latour, 2005; Stevens & Hall, 1998). These theories emphasize the importance of examining reasoning within the sociomaterial context in which it is authentically learned and applied. Therefore, in the present study of spatial reasoning in making, we have focused on: (1) examining the specific interactions between people, tools, and representations through which spatial reasoning is enacted and developed; and (2) tracing specific spatial representations across representational media (e.g., from external representations to mental representations and back), in order to understand how spatial understandings are distributed to or co-constructed by learners and their social and material context.

The analyses presented here are part of a line of work (see also Ramey & Uttal, 2017), which frames spatial reasoning not just as a set of cognitive processes or skills but also as a set of distributed practices, which draw on context- and activity-specific social and material resources (i.e., *distributed spatial sensemaking*). This line of work fills a gap in prior literature in understanding *how* spatial reasoning is used, learned, and can be evaluated qualitatively, within the context of STEAM learning activities. In prior work, Ramey and Uttal (2017) used a combination of qualitative and quantitative analysis to understand and compare the spatial reasoning of youth in a summer engineering camp during different types of engineering activities. They found that construction activities (i.e., building from diagrammatic instructions) elicited different types of distributed spatial sensemaking than did engineering design activities (i.e., brainstorming and prototyping a solution to a problem given constraints). They also found that distributed spatial sensemaking facilitated engineering practices such as hypothesis testing and design iteration. The analyses presented here extend this line of work by examining: (1) how learners make sense of the spatial problems that arise in making activities; (2) what cognitive processes and social and material resources they draw on to do so; and (3) how spatial reasoning develops and supports STEAM problem-solving and learning.

In particular, because making activities rely heavily on spatial representations (e.g., CAD software, programming software, circuit diagrams) and tangible tools (e.g., 3D printers; robots; circuit boards), we believe that the tools and technologies used in a particular making activity could strongly influence what types of spatial reasoning are needed, how they are used, and how they inform STEAM problem-solving and learning. Therefore, one specific focus of this investigation is on the particular tools and representations that accompany different making activities and how students draw upon these resources to solve spatial problems. With this line of inquiry, we hope to contribute to understandings of the role of particular tools, such as CAD software, in improving spatial reasoning, by determining *how* students reason *with* these tools, not just whether their spatial skills might be improved as a result of this interaction.

We also hope to contribute to an understanding of what types of spatial reasoning – both in the cognitive sense and in the distributed sense – matter for STEAM thinking and learning. Therefore, we have employed the analytic framework developed by Ramey and Uttal (2017), which took the cognitive spatial skills and categories of skills compiled by Uttal et al. (2013) and Newcombe and Shipley (2015) in their two by two matrix and translated them into qualitative codes, which could be applied to observable talk or action (for more on this see the Data Analysis section). This approach allows us to address the additional gap in the literature, regarding the role in STEAM learning of types of spatial reasoning other than the intrinsic-dynamic skills typically measured by psychometric tests.

Using data from a cognitive-ethnographic study of middle school students engaged in one set of STEAM-focused, technology-rich, in-school, making activities, we provide detailed descriptions and analysis of student reasoning, which demonstrate: (1) that spatial reasoning was frequent and diverse, going well beyond what would be captured on a standard psychometric assessment; (2) how spatial reasoning was dependent upon the technology tools, representations, and collaboration required for or afforded by different activities (and therefore how it differed by activity); (3) how spatial reasoning developed over time; and (4) how it led to problem-solving insights and learning.

Method

Research Context

The research presented here was conducted in one set of in-school, making contexts, FUSE Studios (Stevens et al., 2016). FUSE provides students with a set of almost 30 STEAM challenges (For a full list, see Table 1). These challenges are designed to be interest-driven, learner-centered, and inclusive of many different types of learners. They are also designed to integrate student interests (e.g., video games, jewelry) with the tools and practices of professionals from different STEAM disciplines (e.g., programming, 3D modelling, and 3D printing). In some challenges, the tools and practices used are specific to one STEAM discipline (e.g., designing a wind turbine), while in others, the tools and practices used might be relevant to multiple disciplines (e.g., 3D modelling and 3D printing). Many challenges also incorporate relevant concepts from specific STEAM disciplines (e.g., science and math concepts). However, the idea is that these concepts would be learned through the making and tinkering activities (e.g., through engineering, arts/design, and work with technology), rather than through reading about them in a textbook or receiving a lecture on them from a teacher. Each challenge has multiple levels of increasing difficulty. So students "level up" like they would in a video game. Students are able to choose which challenges to pursue, according to their interests, and what resources to draw on to complete the challenge. Guidelines and help resources for challenges are housed on the FUSE website (https://www.fusestudio.net). However, the actual challenges are done using a combination of open-source software programs housed on students' local computers (e.g., Sketchup, Stencyl, Inkscape), and physical tools and materials stored in individual FUSE studios (e.g., 3D printers, vinyl cutters, circuit boards).

Insert Table 1 here.

FUSE challenges were designed for fourth- to twelfth-grade students, who are encouraged to explore challenges of interest to them, either alone or with others, and with minimal instruction from an adult. FUSE was originally designed for out-of-school contexts, such as libraries, youth centers, or after-school programs but is now being used mostly in schools, facilitated by a teacher. We chose to explore spatial reasoning in FUSE because of the wide variety of challenges available, the similarity in structure between the challenges, the way in which FUSE allows students to draw on heterogeneous resources for problem-solving, and the fact that students typically participate in FUSE for a full semester or school year. These characteristics make FUSE an ideal context in which to: (1) examine students' spatial reasoning with other people, tools, and representations; (2) compare reasoning with different tools and representations; and (3) examine changes in reasoning over an extended period of time.

Our research was conducted in one set of fifth- and sixth-grade classrooms where FUSE was offered as a year-long class, meeting twice a week for 90 total minutes. These classrooms were all from one large, suburban, Midwestern school district, with a racially and socioeconomically diverse student population.[1] At the time of our observations, only the five STEM-focused elementary schools in the district were running FUSE as an in-school program. The data presented here come from observations of five classrooms, from four of these five STEM-focused elementary schools.

Focal classrooms were chosen to achieve variability and representativeness on specific instructor and student characteristics. First, to ensure a representative picture of how students at different grade levels participated in FUSE activities, our sample was comprised of three fifth-grade classes, one sixth-grade class, and one mixed, fifth-sixth-grade class. Second, in all classrooms, FUSE was facilitated by students' regular classroom teacher. However, to insure a representative picture of the different ways in which FUSE might be facilitated by different teachers, our sample of focal classrooms included two classrooms with teachers who were new to FUSE (one fifth and one sixth), and three classrooms with teachers who had facilitated FUSE before (two fifth and one mixed fifth and sixth).

Participants

Of the 127 students in our five focal classrooms, 90 agreed to participate in this research. Of these, 58 were fifth graders, and 32 were sixth graders; 42 were male, and 48 were female. We could not collect racial demographic information for all students. However, an estimate

[1] The student population in this district is 31 percent low income and 22 percent English language learners. It is 42 percent white, 24.7 percent Latinx, 22.8 percent Asian, 6.3 percent black, 3.5 percent multiracial, 0.4 percent American Indian, and 0.2 percent Pacific Islander.

derived from our observations and from those students for whom we do have this information suggests that the racial composition of our participant group resembled that of the district.

Data Collection

We conducted a cognitive ethnography (Hutchins, 1995a; 1995b; Hollan, Hutchins, & Kirsh, 2000) of classroom activity in the five FUSE studios. Ethnographic observations were conducted during the Spring of the 2014-15 school year and the entire 2015-16 school year. A member of our research team attended every FUSE session and collected field notes, video, and pictures of artifacts. Field notes focused on which challenges students were working on, what resources they were drawing on, what types of problems they encountered, and how they solved those problems. Video was collected using one tripod-mounted, stationary camera, and six point-of-view cameras (small Go-Pro®, Drift®, or Mobius® cameras mounted on tennis visors), worn by six focal students in each class.

Video from the point-of-view cameras was the primary focus of our analysis, as these cameras allowed us to capture the students' perspectives on their own work. These cameras also provided clear audio of the students' conversations and allowed us to follow students' activity as they moved about the classroom (a frequent occurrence in FUSE). On any given day of studio observations, focal participants were chosen to wear visor cameras based on the following criteria: (1) formally consented to participate in research and specifically to wear visor cameras; and (2) informally consented to wear the visor on that day (i.e., asked for a camera or said yes when we asked). As we continued our observations, we also prioritized giving cameras to students who had worn them in the past, so that we could follow their cases over time.

Data Analysis

Initial content-logging of the video data showed that, of the 24 different FUSE challenges available to students during our observations, we had adequate documentation of students doing 18 of them (i.e., at least two students or groups doing the challenge over one or more class periods). For these 18 challenges, we selected two contrasting cases of a student or group doing the challenge. We selected the first case based on the amount and quality of video, privileging cases where students worked most or all the way through the challenge, while wearing a camera. In selecting the second case from each challenge, we chose a case that contrasted with the first case along one or more theoretically important dimensions (e.g., individual versus collaborative, fifth versus sixth grader, or systematic versus tinkering approach). For each case, we analyzed all the video of the student(s) doing the challenge. This ranged from 30 min to 15 hours of video per case, for a total of approximately 88 hours of video.

We analyzed this video using a combination of qualitative categorical coding and interaction analysis. In conducting this analysis, we drew on cognitive-developmental work in which talk, gesture, object manipulation, or sketching have been used as evidence of mental models of spatial phenomena (e.g., Sauter, Uttal, Alman, Goldin-Meadow, & Levine, 2012; Singer, Radinsky, & Goldman, 2008; Vosniadou & Brewer, 1992) and on work demonstrating cognitive and developmental links between spatial reasoning and spatial talk, gesture, or object manipulation (e.g., Göksun, Goldin-Meadow, Newcombe, & Shipley, 2013; Levine et al., 2011; Ping et al., 2011; Pruden et al., 2011). We also drew on situated and distributed work that argues that what we can see from analysis of talk, gesture, and object manipulation is not only the visible residue of internal reasoning processes, but *is* itself reasoning – as reasoning includes the embodied, interactional work of the hands and body (e.g., Stevens, 2012).

In conducting our qualitative categorical coding, we used a modified version of Ramey and Uttal's (2017) coding scheme to code *multimodal idea units* for evidence of distributed spatial sensemaking. This included idea units (Chafe, 1979; 1980) expressed not just through talk, but through any external modality, including talk, gesture, or object manipulation. Codes were based on the recent taxonomy of spatial skills developed by Uttal et al. (2013) and Newcombe and Shipley (2015), which divides these skills into intrinsic-static, intrinsic-dynamic, extrinsic-static, and extrinsic-dynamic skills, identifying specific subskills within each category. We iteratively revised Ramey and Uttal's (2017) coding scheme, in conversation with our data and relevant literature, in order to capture additional types of spatial reasoning in which students were engaging in FUSE, but which were not captured by Ramey and Uttal's original coding scheme. For example, we added codes for quantifying space, scaling or scale changes, mental folding, and describing relative size. We also removed some codes for types of spatial reasoning not observed in our dataset, such as cross-sectioning, locating an object or self with respect to a frame of reference, and alignment (relating different ways of location coding). For a full list of codes with definitions and examples, see Table 2.

Insert Table 2 here.

Drawing on prior work by Hutchins (1995a; 1995b), Goodwin (2000), and Stevens and Hall (1998), we also coded participants' interactions for both the human and non-human resources they drew on to aid in spatial reasoning and problem-solving. These included diagrams, instructional videos, written instructions, other students' talk and gestures, instructors' talk and gestures, tinkering with physical and digital materials, and sketching or working from sketches. For a full list of codes with examples of each, see Table 3.

Insert Table 3 here.

From there, we identified *episodes of distributed spatial sensemaking*. Drawing on Ramey and Uttal's (2017) definition, we defined these as two or more turns of talk or action initiated by a learner asking a spatial question, posing a spatial problem or goal, or presenting a spatial hypothesis. Episodes continued until the question was resolved or the topic shifted. In some cases, in presenting the episodes in the results section here, we've also included a line or two prior to the start of the episode to provide necessary context.

We analyzed these episodes using interaction analysis (e.g., Goodwin, 2000; Hall & Stevens, 2015; Jordan & Henderson, 1995; McDermott, Gospodinoff, & Aron, 1978; Mehan, 1982). We employed this analytic method, in conjunction with categorical coding, because it is the methodological consequence of seeing cognition as socially and ecologically distributed (Jordan & Henderson, 1995). As Jordan and Henderson (1995) wrote, interaction analysis is:

> …the empirical investigation of the interaction of human beings with each other and with objects in their environment…[investigating] human activities, such as talk, nonverbal interaction, and the use of artifacts and technologies, [and] identifying routine practices and problems and the resources for their solution (p. 39).

Consequently, interaction analysis not only aligns with situated and distributed theoretical lenses on learning but also has unique affordances for understanding how thinking and learning unfold in moment-to-moment, multimodal interactions between people, objects, and representations. Specifically, by applying Schegloff's (1992) principals of *relevance* and *procedural consequentiality*, interaction analysis allowed us to engage in a turn-by-turn analysis of how distributed spatial sensemaking unfolded in context. As a result, while the categorical coding scheme we used allowed us to determine *what* types of cognitive spatial processes, practices, and resources student drew on during FUSE activities, interaction analysis allowed us to see *how* these processes, practices, and resources mattered for sensemaking and problem-solving.

Results

Our analyses yielded four findings related to spatial reasoning and STEAM learning in the context of FUSE activities. First, they show that in making sense of and working through FUSE challenges, students engaged in frequent and diverse forms of spatial reasoning and drew on a variety of both social and material resources to do so. Second, they show how the different sociomaterial contexts and task constraints of different FUSE challenges facilitated different types of distributed spatial sensemaking. Third, they show how spatial reasoning developed over time, and fourth, they show how spatial reasoning led to STEAM problem-solving insights and learning that advanced challenge work.

Students Engaged in Frequent and Diverse Spatial Reasoning with a Variety of Resources

Through categorical coding of multimodal idea units, we found 9393 instances of spatial reasoning demonstrated through talk, gesture, or object manipulation – an average of over 100 per hour or almost two per minute. Students engaged in 13 different types of spatial reasoning, spanning all four quadrants of the two by two matrix (see Figure 1). The most commonly used were extrinsic-static skills (57 percent of instances of spatial reasoning), followed by intrinsic-static (24 percent), extrinsic-dynamic (11 percent), and intrinsic-dynamic skills (8 percent).

Insert Figure 1 here.

There are three things that are important to highlight in these findings. The first is the very large number of instances of spatial reasoning (9393 instances, 100 per hour). The second is the broad range of different spatial skills students used. The third is the relative infrequency of intrinsic-dynamic spatial reasoning, relative to other types of reasoning (only 8 percent or 713 instances). In other words, not only is it clear that making activities like those in FUSE require spatial reasoning, but the spatial reasoning required goes well beyond the intrinsic-dynamic reasoning most often measured by psychometric tests. This means that by relying only on these tests, we're missing a lot of what's going on in real-world problem-solving contexts.

In making sense of the spatial aspects of FUSE challenges, students also used a variety of social and material resources, in coordination with one another. Social resources included other students (44 percent of total instances of resource use) and adults (9 percent). Material resources included help videos (10 percent), written instructions (7 percent), and diagrams from the FUSE website (3 percent), tinkering with physical or digital materials (28 percent), and sketching or working from sketches (1 percent). For examples, see Table 3.

It is important to notice that many of the resources that students used were highly spatial, including help videos, diagrams, sketches, and physical and digital materials. Others, such as other students, adults, and written instructions, were not inherently spatial but were able to convey spatial information through talk, gesture, and object manipulation. Again, this indicates what we are missing from laboratory or correlational accounts of spatial reasoning that strip away these important aspects of social and material context. It is also noteworthy how infrequently students drew on adults as a resource, relative to other resources in the room. This is important, as it emphasizes the contrast between the didactic instructional approaches used in many spatial training interventions and the way in which spatial reasoning is elicited during making activities.

Different Challenges Facilitated Different Types of Spatial Reasoning

Our analyses also showed how different FUSE challenges elicited different types of distributed spatial sensemaking. For example, Figure 2 shows the relative frequency of different types of spatial reasoning demonstrated during different challenges (for descriptive statistics, see also the Appendix). There are two things that are important to highlight here. First is the relative frequency of both intrinsic-dynamic and extrinsic-dynamic reasoning in FUSE challenges involving CAD software (e.g., *3D You, Keychain Customizer, Print My Ride, Eye Candy, Dream Home,* and *Dream Home 2*). This indicates the importance of particular technology tools in facilitating particular types of spatial reasoning. Second is the relative frequency of extrinsic-dynamic reasoning in challenges, such as *3D You* and *Get in the Game*. We argue, based on interaction analysis of episodes of distributed spatial sensemaking, that this was because these challenges, in particular, required the coordinated movement of multiple people, physical and digital representations, and objects simultaneously, in order to complete the challenge. This is important, because it suggests design principles for activities that engage students in extrinsic-dynamic spatial reasoning.

Insert Figure 2 here.

Spatial Reasoning with CAD Software. The relative prevalence of both intrinsic-dynamic and extrinsic-dynamic spatial reasoning during challenges involving CAD software is interesting for two reasons. First, it highlights the spatial complexity of designing with these sorts of tools. Second, the ways in which students used these types of spatial reasoning, particularly perspective taking (extrinsic-dynamic) and mental rotation (intrinsic-dynamic), while designing in the CAD tool, Sketchup, highlights the importance of specific tools and representations in shaping students' spatial reasoning.

For example, in the *Dream Home* challenge, students are asked to build and furnish a CAD model home in the software program, Sketchup. While working on this challenge, students' design goals frequently required them to change perspective on their model home in the software, using the "orbit" tool to see the home from different sides. As we can see from the case of one student, Johanna, failure to do so led to problems. In the episode presented in Figure 3, Johanna had just added an extra wing to her CAD model home, in the shape of a stacked pyramid (line 1). However, because when she had created it, she had been looking at her house from above, she had accidentally created it on an angle, rather than flat on the ground (lines 1-2). When she finally did change perspectives on her model home, she realized her mistake (line 2), and was initially frustrated (lines 4 and 6).

Insert Figure 3 here.

However, after Johanna's initial frustration, she decided that she liked the diagonal structure. In fact, she liked it enough that, after accidentally closing her file without saving it, she decided she wanted to recreate it (see Figure 4). In doing so, she was forced to employ perspective taking to figure out how she had created it in the first place. We can see from the interaction in Figure 4, that while looking at her home from the side, she was initially unsure how to recreate the pyramid (line 1). However, once she changed perspective to look at the house from above (line 3) – the direction from which she'd been viewing it when she'd made it before – she was able to redraw the base for her pyramid (line 4). It wasn't until after she had celebrated her success (line 4) that she changed perspectives to a side view to actually confirm that the base was on a diagonal, rather than flat on the ground (line 6). Her premature celebration suggests that, at this point, she still did not understand that a square on a diagonal and a square flat on the ground should look the same from above. However, the fact that she knew to check the side view afterward suggests a developing understanding that looking at the structure from different perspectives might provide additional information not provided by the top view alone.

Insert Figure 4 here.

This example from Johanna's work on the *Dream Home* challenge demonstrates the importance of spatial reasoning and understanding spatial representations for working in Sketchup. Specifically, it shows how the "orbit" tool helps users engage in the extrinsic-dynamic skill of perspective taking, but only if they understand the information provided by different perspectives and the relations between them well enough to make use of the tool.

The transcripts in Figures 5 and 6 highlight the way in which a different tool in Sketchup, the "rotate" tool, elicited the intrinsic-dynamic skill of mental rotation. These transcripts show a conversation between two students, Evan and Victoria, which took place while Evan was trying to rotate furniture around inside of his model home. At the start of this interaction, Evan had downloaded models of a television and a couch, in order to furnish the home he'd designed. However, when he'd initially placed the two models into his home, the TV was perpendicular to the couch. So he was trying to figure out how to make it parallel (across from it). He enlisted the help of Victoria, who was sitting next to him and also working on *Dream Home.*

Insert Figures 5 and 6 here.

In the interaction in Figures 5 and 6, we can see that Evan used the orbit tool to change perspectives on his model home like Johanna did (line 3). However, we can also see from the language and gestures that he used to describe how he wanted to move the couch (line 1), that he was also engaging in mental rotation (e.g., "How do you like rotate it like to be..."). In lines 3 and 5, we can see from his language and gestures, that he was visualizing how he wanted the couch to be positioned relative to the television but was unsure of how to use the tools in Sketchup to move it there. Then, in line 6, Evan was able to use Victoria as a spatial problem-solving resource. She pointed him to the rotate tool to change the orientation of his television. Using this tool forced Evan to explicitly think in terms of mental rotation, because the rotate tool requires the user to place the tool on a specific axis (x, y, or z), and then rotate the object in a circle on that axis. This appeared difficult for Evan, as after multiple attempts (lines 9, 14 and 17), he still hadn't figured out how to rotate the television around the right axis to get it where he wanted. It wasn't until a few moments later, in the interaction depicted in Figure 7, that with Victoria's help, Evan finally figured out how to rotate the television the right direction.

Insert Figure 7 here.

At the opening of the interaction in Figure 7, Victoria took over Evan's mouse (line 1) and changed perspective on the room using the "orbit" tool (line 3). After being briefly interrupted by Evan taking back the mouse and using the "move" tool to move the television forward and backward (line 4), Victoria's new perspective on the television helped her figure out how to place the rotate tool on a different axis to rotate the television left and right, rather than forward and backward (line 5). From there, Evan was able to figure out how to place the tool on the right axis to rotate the television up against the wall (line 6).

In both Johanna's and Evan and Victoria's cases, the different types of spatial reasoning in which students engaged both supported and were supported by the use of the tools in Sketchup (orbit or rotate). They were also elicited by the task constraints of the challenge (creating and furnishing a model home in virtual three-dimensional space). In Johanna's case, we saw how the "orbit" tool helped users engage in perspective taking, as long as they understood the relations between different perspectives well enough to make use of the tool. In Evan's case, we saw how the rotate tool forced users to be explicit, not just about where they envisioned putting an object, but about the process of rotation required to get it there, particularly the axis around which the object must be rotated. This sort of understanding of the ways in which particular tools, representations, and activities (particularly ones related to the practices of STEAM professionals) are supported by but also shape spatial reasoning is one important relative advantage of looking at spatial reasoning qualitatively, in the context of real-world thinking and learning activities, using the tools of STEAM professionals.

Spatial Reasoning in FUSE Challenges Requiring the Coordination of Multiple People, Tools, and Representations. The importance of particular tools and task constraints in facilitating particular types of spatial reasoning is further highlighted by two challenges, *3D You* and *Get in the Game,* which require the coordinated movement of multiple people, physical and digital representations, and objects simultaneously, in order to complete the challenge. In both of these challenges, we observed correspondingly high frequencies of extrinsic-dynamic spatial reasoning. For example, the transcript in Table 4 and image in Figure 8 show an interaction between three students, Tia, Kyle, and James, as they worked together to do the last level of *3D You*. The goal of this challenge level was to use a Kinect to scan a 3D image of one student's (James') head into a software program, so that he could 3D print a bust of himself. In order to do this, students needed to use the Kinect to scan James' head from every angle, so that the software program had enough information to render all sides of the 3D bust. This was tricky, both because it required figuring out how to move the student and/or the Kinect to complete the scan, and because, in order for the software program to process the information being inputted from the Kinect, all movements had to be slow and incremental.

At the opening of the interaction in Table 4, the students were almost done scanning James' head. All that was left was to scan the top of it. Kyle had been holding the Kinect, while James, seated in a spinning desk chair, revolved slowly in a circle. However, at the opening of this episode, Tia, who had been sitting at the computer, monitoring the representation of James' head on the screen, offered to switch places with Kyle and hold the Kinect (see Figure 8).

Insert Figure 8 here.

Insert Table 4 here.

In this episode, we can see that for the activity to proceed successfully, the participants in the interaction (Kyle, James, Tia, the Kinect, the computer, and the desk chair) needed to both think spatially and coordinate spatial representations across different representational media (gesture, talk, body position, and the computer display) in the distributed cognitive system. In doing so, they engaged in many extrinsic-static and -dynamic types of spatial reasoning. For example, in line 1, Tia took the Kinect from Kyle and attempted to replicate the position in which he was holding it (requiring reasoning about static spatial relations). Then in lines 2, 4, and 6, Kyle engaged in reasoning about static and dynamic spatial relations in order to coordinate the representation on the computer screen with James' position and the position of the Kinect. To do so, he gave James verbal and gestural instructions to move in different directions, so that his head would be properly aligned with the guide on the computer screen.

By line 9, James' head was aligned with the guide on the screen, but Kyle's attempt to coordinate the representation on the screen with the position of James' body continued, as he attempted to figure out who or what needed to move, in order to capture the top of James' head.

After posing the question, “Now how do we get the top of his head?”, Kyle said “Because if you try to pick it up, it just says go back to last pose.” Here, the “it” to which he was referring was the Kinect, which the students had discovered earlier in this activity could not itself be moved too quickly, or it would generate the error message, “Go back to last pose.” In line 9, James proposed a solution to this problem by moving his body instead of the Kinect, leaning forward so that the Kinect could see the top of his head. Here, both Kyle and James used perspective taking to envision what the Kinect could see and what would be represented on the screen. They also needed to reason about static and dynamic spatial relations to figure out who or what needed to move and in what direction. Tia also engaged in perspective taking and reasoning about dynamic spatial relations (line 10) by saying to James, “Now circle around holding your breath.” In line 12, James heeded her instructions by turning slowly in a circle, indicating that he’d understood the spatial information she was conveying via talk and translated it into body movement. Then in line 13, Kyle continued giving instructions to James on how to move, based on what he was seeing on the computer screen, and James continued interpreting and acting on this information. Finally, in line 18, after James’ head had fallen out of alignment with the guide on the screen and rotated 90 degrees, Tia engaged in additional perspective taking, moving the Kinect to realign James’ head with the guide. When this didn’t work, James got up (line 19) and proposed watching the video (to see if they’d gotten what they needed before his head fell out of alignment).

This episode shows how the successful completion of the 3D You challenge necessitated the communication of spatial representations across representational media in a distributed cognitive system. The dynamic coordination of multiple tools, representations, and people required extrinsic-static and -dynamic spatial reasoning. In contrast to prior approaches to improving spatial reasoning through teacher-led instruction or training exercises, this episode shows how an activity itself can elicit the use of particular spatial skills and practices.

How Spatial Reasoning Developed Over Time

In each of the episodes that we've presented thus far, interaction analysis has shown us how students used spatial reasoning, in conjunction with particular social and material resources, to solve challenge-related problems. On a microgenetic level, the way in which reasoning progressed, through iterative problem-solving attempts, during these short interactions, in itself represents learning. However, interaction analysis of spatial reasoning during FUSE challenges also demonstrates how learning occurred over the longer term, in two important ways.

First, we observed students' spatial reasoning developing over time. To understand how, we'll revisit Johanna's work on the *Dream Home* challenge. The reader will recall that in the interaction depicted in Figure 3, Johanna's failure to engage in perspective-taking led her to mistakenly build an addition to her model home on a diagonal rather than flat on the ground. Then in the interaction in Figure 4, after accidentally deleting that addition to her home, she began to engage in perspective taking, in order to recreate the structure, but still wasn't fluidly transitioning between views and understanding what each could and couldn't show her.

However, after these interactions, which took place in late October (approximately one month into Johanna's time in FUSE), she continued working through the levels of the *Dream Home* challenge. By late January, she had completed all three levels and moved on to *Dream Home 2: Gut Rehab,* which also uses Sketchup, but asks students to renovate and customize a CAD model home for a client, rather than designing and furnishing their own model home. The interaction depicted in Figure 9 demonstrates how, by the time she had started *Dream Home 2:*

Gut Rehab, Johanna's perspective taking skills had improved, so that she was better able to take advantage of the "orbit" tool to obtain needed spatial information.

Insert Figure 9 here.

In the interaction depicted in Figure 9, we can see how, after an initial plea for assistance from her friend, Victoria (line 1), Johanna was able to independently use the "orbit" tool in Sketchup to select appropriate perspectives on her home to place a rug flat on the floor. For example, immediately after moving the rug in line 1, she changed perspectives to a side view, to see if the rug was on the floor (line 2). Once she had confirmed that it was, she switched back to the top view (line 3). However, from that perspective she noticed a different problem, that the rug was *in* the floor (indicated by Sketchup through the partial transparency of the rug shown in line 3). Based on this information, Johanna pulled the rug up until it was no longer transparent, then immediately orbited to the side view again (lines 4 and 5). She observed that the rug was now floating in midair. So, continuing to look at it from the side, she lowered it back down.

Unlike in Johanna's earlier interactions with the tools in Sketchup, during this interaction, she was able to transition *purposefully* between views to accomplish the task at hand. This showed not only a developed understanding of the tools and representations in Sketchup, but also a developed ability to engage in the perspective taking needed to know what could and could not be seen from each view of the rug. In other words, it is because of developments in her spatial reasoning that Johanna was able to make use of the "orbit" tool efficiently and effectively here, and it is through the repeated use of these same tools, that her spatial reasoning developed.

Spatial Reasoning Led to Problem-solving Insights and the Learning of Concepts from STEAM Disciplines

The other way in which spatial reasoning during FUSE challenges led to learning was by supporting problem-solving insights and the learning of relevant concepts from STEAM disciplines. This is best illustrated by the cases of Adele, Anna, and Carmen working on *Spaghetti Structures* and Erin, Ajay, and Aiden working on *Solar Roller*. For example, as Adele et al. worked through *Spaghetti Structures*, their spatial reasoning supported math problem-solving insights and the discovery of math concepts. This is because the goal of *Spaghetti Structures* is to build the tallest possible structure with a finite set of materials. Therefore, one of the requirements to complete each challenge level is to measure the height of one's structure. For fifth graders just learning about 3D geometric concepts, like area and volume, and not yet familiar with concepts like the Pythagorean Theorem, this appeared somewhat difficult. In the transcript in Table 5, we can see how Adele and her classmates coordinated spatial and mathematical reasoning as they struggled to figure out how best to measure the height of Adele's spaghetti structure.

Insert Table 5 here.

In this episode, Carmen began by holding up the measuring tape on a diagonal, rather than straight up and down and looking at the wrong end of the measuring tape (lines 2 and 5), so that she measured the structure as "2 inches" tall. Adele rejected Carmen's measurement of "2 inches" by saying "let me see it" (line 6) and tried a measurement of her own. However, she also measured on an angle and only measured one piece of spaghetti at a time, yielding multiple measurements of 10 inches, rather than one measurement of the total height (lines 6 and 8).

A few moments later (as shown in Table 6), Adele sought help from the first author (line 1), and when the researcher asked her how tall the structure was (line 4), she reported the measurements of individual pieces of spaghetti in both inches and centimeters (line 5). Then, when the researcher asked her which one was the height, she said “10” (line 6), which wasn’t the height of her structure, but made sense when, in response to the researcher asking her, “So what would we measure on here to find the height?” (line 7), she replied “The triangles?” (line 8), because 10 was the length of one side of each triangle (one piece of spaghetti). When the researcher followed up by asking her how she might measure the total distance from the bottom to the top of her structure (lines 10, 12, 14, and 16), she moved away from the triangle measuring method but still measured on a diagonal, rather than straight up and down. Then, in line 21, Anna joined the interaction and introduced the idea that they could measure the structure on the other side, arguing, “That's the straightest part,” (line 22). Adele did that but still measured on an angle up the side of the triangular structure, rather than straight up from the center bottom of the structure (line 23) and got a measurement of 19 inches, which Anna agreed was correct (line 25). Neither girl seemed to understand yet why this measurement was problematic.

Insert Table 6 here.

In a later class period, when Adele and Anna went to measure another spaghetti structure they’d created, things unfolded differently (see Table 7). In this episode Adele began measuring in the same way she had been in the previous episode, on a diagonal up the side of the structure (line 1) and only measuring part of the structure, not the whole thing (line 3). Anna corrected her (line 4) by proposing an idea that she had had in the previous episode, that there was a “tallest side” of the structure and suggesting that Adele measure that instead (line 4). This prompted a measurement of 7 inches from Adele in line 5, which was questioned by Anna in line 6.

Insert Table 7 here.

Then in line 7, Mr. Lewis entered the interaction and corrected them, explaining, through talk and gesture, that they should measure straight down, rather than on an angle (lines 7 and 10).

The girls measured the structure the way that he had instructed and got a measurement of 10 inches (lines 11 and 12). When he asked them “Why do we not measure on the angle?” (line 13), Anna correctly answered, “Because then you get a bigger measurement” (line 14), and in response to his question about whether this would be accurate (line 15), Adele said no (line 17), and Anna said it wouldn’t be fair (line 16). Figure 10 summarizes the different ways in which the girls attempted to measure their spaghetti structures and the progression over time.

Insert Figure 10 here.

In these episodes, we can see how the particular constraints of a challenge like *Spaghetti Structures* (trying to make the tallest tower) encouraged students to integrate mathematical reasoning with reasoning about spatial relations between objects (the measuring tape, spaghetti structure, and table). Although this wasn’t easy at first, through feedback from each other and adults, they were able come to spatial understandings of mathematical principles (e.g., the hypotenuse being longer than the legs of a triangle). In the context of FUSE activities, when mathematical concepts were invoked, they were almost always used to quantify space. Students engaged in mathematical reasoning, like spatial reasoning, not because they had been assigned to learn a particular math concept, but because it was necessary to solve a problem. This authentic and applied use of mathematics, supported by spatial exploration, contrasts with the abstract, decontextualized ways in which math is often taught in schools.

A second example of spatial reasoning leading to problem-solving insights and the discovery of concepts from STEAM disciplines comes Erin, Ajay, and Aiden working on the *Solar Roller* challenge. The broad goal of this challenge is to build a solar car capable of travelling a fixed distance along a track. In the first level, students are instructed to assemble a basic solar car, shine a light on it, and see if they can get it to run for 60 inches. In the second level, they are shown (via diagrams and videos) how to incorporate a capacitor into their solar car and asked to build a 50-inch tunnel, 40 inches from their starting line, so that the car has 40 inches to run with a light shining on it but then must run another 50 inches on stored energy.

During the second level of the challenge, there were three specific problems that spatial reasoning allowed Erin, Ajay, and Aiden to solve. The first was how to create a 50-inch-long tunnel. The second was how to wire a capacitor into their car, and the third was how to get their car across the finish line. The solution to each of these problems hinged on spatial insights, as did the discovery of math, science, and engineering principles that occurred along the way.

In the interest of space, we won't go into detail on how the students used spatial insights to solve the first problem of creating a tunnel, focusing instead on problems two and three. We have, however, included images of the three iterations of their tunnel design (see Figure 11), each of which involves different materials configured into a different spatial arrangement, but all of which met the requirements of a 50-inch tunnel. This is indicative of another integration of spatial and mathematical reasoning, as well as an iterative engineering design process.

Insert Figure 11 here.

A second problem that the students solved using spatial insights was the problem of how to add the capacitor into their solar car. As the interaction in Table 8 shows, to solve this problem (presented by Erin in line 2), the students used help videos and diagrammatic instructions from the FUSE website (lines 2, 11, 15, 17) to figure out how to correctly reconfigure their car. In order to make use of these visual instructions, the students needed to engage in disembedding to identify different parts of the diagram and car, 2D to 3D translation to translate between the diagram and the car, and thinking about spatial relations between different pieces in order to assemble them. The students also tinkered with the parts of the car. This required them to engage in disembedding to identify different parts of the car, to reason about extrinsic-static spatial relations between different pieces (e.g., line 11, "…so the solar panel's right here. The motor's right here.") and to reason about relative size (e.g., line 3, "The big one. This one's the positive side." And line 17 "Ok so this is the capacitator, and it would, short leg on the capacitor").

Insert Table 8 here.

Through this problem-solving process, the students not only managed to solve the problem at hand – correctly installing the capacitor into their solar car – but they also came to a spatial understanding of electrical circuits and the function of capacitors in them. We can see this where Ajay asked "What's a capacitator?" (line 18), and Erin answered "Um, it like gives energy, a short burst of energy, once the light disappears, continues the loop". Not only did she provide a fairly accurate, functional definition of a capacitor here, but it's also one that incorporates a description of the spatial arrangement of a circuit and the capacitor's role in it ("continues the loop"). In other words, this example shows how spatial reasoning during FUSE not only facilitated problem-solving but simultaneously supported the learning of a science and engineering concept (e.g., what a capacitor is and how it works). This is demonstrated by both the fact that Erin and her teammates were able to correctly install the capacitor and the fact that Erin was able to explain its function.

A final example of problem-solving from the Erin, Ajay, and Aiden's work on Level 2 of *Solar Roller* that further illustrates how spatial reasoning supported problem-solving and learning comes from their solution to the problem of getting their car across the finish line. The interactions depicted in Tables 9 and 10 show how they made a key realization, that the carpet didn't provide an ideal surface for a racetrack and why this realization was consequential.

Once the students had set up their original tunnel made out of chairs and wired the capacitor into their solar car, they tested their car on the floor, as shown in Table 9, line 1. However, the car didn't work (line 1). Ajay looked at the car and, using disembedding (intrinsic-static reasoning) and reasoning about spatial relations (extrinsic-dynamic reasoning), diagnosed the problem as a problem with the spatial configuration of the motor relative to other parts of the car (line 5). So he moved the motor, and the wheels began spinning in midair (line 5). Ajay continued examining the spatial configuration of the car (lines 12 and 15) and tested the car in midair with the light turned off to confirm that the capacitor was doing its job of storing and deploying energy after the solar energy source was removed. Then, after seeing that everything seemed to be working properly in midair, Erin proposed an alternative hypothesis for why the car wasn't reaching the finish line, saying "Maybe it's the carpet? Maybe we should put paper on the bottom. Or on a smoother surface?" (line 16). This observation was also contingent on reasoning about static- and dynamic-spatial relations (i.e., observing that when the car was in the air, the wheels spun quickly). In other words, in this interaction, not only did spatial reasoning help Ajay eliminate variables, like the relative position of the various parts of the solar car, but it supported the generation of Erin's hypothesis ("Maybe it's the carpet?") and her proposal of a potential solution ("Maybe we should put paper on the bottom. Or on a smoother surface?").

Insert Table 9 here.

After this interaction, the students first tried Erin's first suggestion of putting paper down on the floor, then later, after the paper didn't work much better, they tried her second suggestion of a "smoother surface" by testing their car on a smooth countertop. As they tested Erin's first idea, the paper, their teacher, Ms. Vonn, came over and put a scientific label on the physics concept they had just discovered on their own, saying "So in your notes section, you want to put that down, that there was too much friction on the carpet so to make it go smoother, you added the paper." This not only shows how spatial reasoning can support problem-solving and the discovery of scientific concepts but also suggests an alternative role for teachers in supporting learning. Here, Ms. Vonn wasn't lecturing on a science concept. Instead, she was helping students make connections between the concepts they had discovered themselves during authentic problem-solving and disciplinary concepts and vocabulary.

In other words, throughout their work on the *Solar Roller* challenge, spatial observations, spatial reasoning, and spatial insights were critical to helping Erin, Ajay, and Aiden advance through the levels of the challenge. These spatial insights also helped them "discover" scientific concepts like friction. However, it wasn't cognitive spatial processes alone that led to these moments of insight and problem-solving, but instead, the coordination of internal spatial representations with external tools and representations shared among the three students working on the challenge, truly *distributed spatial sensemaking*.

Discussion

This qualitative analysis of spatial reasoning in FUSE has shown how a different theoretical lens on spatial reasoning, and accompanying methods, improves our understanding of *how* young people reason spatially with the resources used in making activities and *how* spatial reasoning matters for STEAM learning. It also provides an alternative model for improving spatial reasoning – through hands-on, collaborative problem-solving with spatial tools and representations, rather than through spatial training exercises or didactic instruction. Specifically, the findings we've presented here make four contributions to the literature.

First, we showed *that* spatial reasoning occurred in these making activities and *that* it was frequent and diverse. Second, we showed *how* this reasoning was dependent upon a wide variety of social and material resources. As a result, we have shown what the field has been missing by using psychometric assessments and laboratory experiments to isolate cognitive spatial processes from the social and material contexts in which they would normally take place. Such accounts, which have tended to focus on a limited number of (mostly intrinsic-dynamic) spatial skills miss the diverse types of spatial reasoning relevant to STEAM learning. They also miss the important ways in which spatial reasoning in real-world, STEAM learning contexts is supported by coordination across a diverse set of tools, representations, and people. This emphasizes the need for future qualitative or mixed method studies of spatial reasoning within real-world learning contexts, to supplement insights gained from correlation studies and experiments.

Third, we demonstrated *how* different FUSE challenges with different tools and representations elicited different forms of spatial reasoning. For example, we showed how the *Dream Home* challenge encouraged students to engage in intrinsic-dynamic (mental rotation) and extrinsic-dynamic (perspective taking) spatial reasoning *with* the tools and representations in the CAD software program, Sketchup. We also showed *how* the need to coordinate multiple people, tools, and representations for the *3D You* and *Get in the Game* challenges required students to engage in extrinsic-dynamic spatial reasoning and to be able to communicate that spatial reasoning across representational media in a distributed cognitive system. This emphasizes the important role that technology tools and representations can play in both eliciting and shaping different forms of spatial reasoning.

Fourth, we showed *how* spatial reasoning during these activities led to two important types of learning. First, we demonstrated *how* students' spatial reasoning developed over time – through iterative problem-solving attempts and continued work with tools and activities that elicited particular types of reasoning. We saw this both at the microgenetic level – in the progression of reasoning during iterative problem-solving – and on larger timescales, spanning days, weeks, and months. This analysis provides a missing account of *how* spatial skills might be learned in everyday life and provides an alternative model for cultivating them in schools – through hands-on making activities, rather than training exercises or didactic instruction.

The second form of learning we documented was the way in which spatial reasoning led to problem-solving insights and the learning of concepts from STEAM disciplines. For example, students' spatial insights during the *Spaghetti Structures* and *Solar Roller* challenges led to iteration, design insights, and the 'discovery' of math and science concepts like the geometric properties of triangles and the function of a capacitor. As a result, the findings presented here improve our understanding of *what* is learned in making activities and *how* that learning happens. They also speak to the broader question of *how* spatial reasoning supports thinking and learning in STEAM fields and what we are missing by concentrating instruction in verbal and analytic domains.

Implications

These findings, regarding spatial thinking and learning and the role of particular social and material resources involved in that learning, have important implications both for the design of learning activities and environments and for how we think about supporting participation in STEAM disciplines. First, our findings provide further, empirical support for the promise of hands-on making activities for learning. Specifically, they suggest that making activities like those found in FUSE have the potential to be a context where young people could start to build the spatial reasoning skills they need for later success in STEAM fields. More specifically, our findings regarding the role of different tools and representations in facilitating different types of spatial reasoning improve our understanding of the advantages of providing students with access to the particular technology tools available in makerspaces, such as 3D printers and CAD software. Therefore, these findings may also serve as a guideline for educators in selecting and organizing learning activities to facilitate the development of particular types of spatial reasoning.

These findings also have implications for future research on spatial reasoning. Not only do the methods used and findings presented here suggest the benefit of adding qualitative analyses to the repertoire of methods used to study spatial reasoning. They also suggest ways in which qualitative and quantitative or situated-distributed and cognitive analyses of learning might be used in complementary ways to provide a more a complete understanding of spatial reasoning and its role in learning. For example, one might compare performance on situated spatial problem-solving tasks with performance on psychometric tests to better understand the relation between cognitive spatial skills and distributed spatial sensemaking and problem-solving practices. One might also use the findings presented here regarding the importance of different types of spatial skills and social and material resources to design more and different types of psychometric tests that cover a more complete range of types of spatial reasoning. Finally, there are interesting ways in which new technology might be used to provide mixed methods accounts of spatial reasoning that capture both internal cognitive processes and the use of context-specific social and material resources. For example, the field of multimodal learning analytics has shown promise in using technology to capture and quantitively analyze talk, inflection, gesture, gaze, reaction time, and biometrics in real world learning contexts and to integrate this data with screen capture video or web log data to say something about thinking and learning. Although these methods alone have not advanced to the point of being able to provide complete accounts of reasoning in context, if paired with and informed by qualitative analyses of the same phenomena, they have the potential to greatly expand our study and understanding of spatial cognition.

Limitations and Open Questions

However, there are limitations of the current study and still many open questions regarding the role of spatial reasoning in STEAM learning. First, as a qualitative analysis of spatial reasoning in the wild, this study is able to provide insights into *whether* and *how* spatial reasoning was used in our particular research context. However, the lack of control over things like students' choice of challenges, inherent in doing ethnographic work, paired with the need to emphasize depth over breadth in qualitative analysis, puts limitations on the sorts of claims to representativeness or generalizability that this work can make, relative to quantitative work. We propose that this is another place where qualitative and quantitative researchers could work together – pairing qualitative analyses of *how* spatial reasoning is used and learned in context with quantitative analyses of when, for whom, and to what extent experiences like the ones students engage in during FUSE broadly lead to measurable improvements in reasoning.

Second, given that the spatial reasoning that we documented here developed through work with particular tools, we might wonder whether improvements in reasoning might transfer to work in other contexts. Some cognitive research has addressed the question of whether training of cognitive spatial skills transfers to different problem contexts using different spatial skills (for a recent review, see Uttal et al., 2013). However, little research has examined how or whether students are able to apply distributed spatial reasoning practices learned in one context to problem-solving in another context.

Third, although we found that, in order to solve the STEAM problems in this context, students engaged in many different types of spatial reasoning, we don't know whether all would be equally relevant for professional practice in STEAM disciplines or whether there are differences between STEAM disciplines in which would be most useful. Stevens and Hall's (e.g., Stevens, 1999; Stevens & Hall, 1998) research on the professional practices of architects and engineers speaks somewhat to these issues, from a situated and distributed perspective. However, more research that integrates cognitive perspectives with situated and distributed ones and examines these questions across multiple STEAM disciplines is needed.

Further, the sorts of scientific and mathematic concepts that students 'discovered' while reasoning spatially through design problems beg the question, 'What if students get it wrong?' Unlike when teachers feed students the answers, if they are left to 'discover' math and science concepts themselves, they may draw false conclusions or not make connections to math and science at all. One answer to this last question is that even if students don't fully 'get' a math or science concept related to their project work, at the very least, they are gaining an embodied, spatial foundation that might support future conceptual learning in a more formal STEAM learning context. Another is that the activities themselves will let them know if they've understood a concept correctly, because the tools and materials give them immediate feedback as to the accuracy of a hypothesis or efficacy of their solution.

However, perhaps more importantly, in the process of discovering disciplinary concepts and solving disciplinary problems, students are being provided with *an alternative way to reason about STEAM problems generally*, that if they are able to apply it to novel problems and contexts could be a powerful tool for future problem-solving and learning. In this sense, our investigation of spatial reasoning in making activities shows spatial reasoning to be another meta-disciplinary skill, like so-called "21st century skills" (e.g., creativity, adaptive problem-solving, collaboration, and critical thinking) that making activities may be better positioned to cultivate than traditional, more siloed, disciplinary education (e.g., Hilton, 2010). As such, the methods that we've used to investigate spatial reasoning in making provide a template for the investigation of the ways in which these other meta-disciplinary skills are learned and support problem-solving in making activities, as well.

Conclusion

In summary, by drawing on research from different theoretical and methodological traditions and taking a qualitative, rather than quantitative approach to studying spatial reasoning, we've been able to fill in some important gaps in the prior literature, regarding how young people reason spatially, how this spatial reasoning develops over time, and how it leads to STEAM learning. By showing how the making activities in FUSE elicited and helped students develop both spatial reasoning and other, related forms of STEAM learning, we've not only contributed to the literature on what and how learning happens in making activities, but we've contributed to the broader literature on spatial thinking and learning and its role in STEAM learning. In doing so, we've shown how qualitative methods, such as cognitive ethnography, qualitative coding, and interaction analysis can be used to complement quantitative studies of spatial reasoning, in order to provide a more complete understanding of this phenomenon.

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Table 1

List of FUSE Challenges by Category, with Number of Levels and Descriptions for Each

Challenge Type	**Challenge**	**Number of Levels**	**Description**
CAD Challenges	Dream Home	3	Learners design CAD model homes in Sketchup.
	Dream Home 2: Gut Rehab	4	Learners modify existing CAD model homes, given "client's" design constraints.
CAD 3D Printing Challenges	Jewelry Designer	3	Learners design earrings, a bracelet, or a pendant in Sketchup and print them using a 3D printer.
	Print My Ride	3	Learners use images of cars to design model cars in Sketchup and print them using a 3D printer.
	Eye Candy	3	Learners use images to design glasses/sunglasses in Sketchup and print them using a 3D printer.
	Keychain Customizer	3	Learners design keychains in Tinkercad and print them using a 3D printer.
	3D You	3	Learners use Meshmixer to make CAD model animals, then use both Meshmixer and a Kinnect or model and print their own busts.
Computer Programming	Game Designer	4	Learners use Stencyl and basic programming skills to customize and create video games.

and Robotics Challenges	How to Train Your Robot	4	Learners program a Sparki robot to walk, bark, draw, and fetch treats.
Graphic Design and Animation	Selfie Sticker	3	Learners use Inkscape graphic design software to design vinyl stickers and print them using a vinyl cutter.
Challenges	Minime Animation	4	Learners use 3D animation software to bring a CGI character to life, as they customize its colors and expressions and make it dance.
Electronics Challenges	Electric Apparel	4	Learners create circuits out of conductive materials to create light-up clothing.
	LED Color Lights	5	Learners create circuits to power colored LED lights.
	Party Lights	4	Learners use an Arduino to program moving light displays.
	Crystal Ball	3	Learners use an Arduino to program colored light displays inside a crystal ball.
	Music Amplifier	3	Learners use electronic circuit components to create a music amplifier for use with an MP3 player and speaker.
	Get in the Game	3	Learners use a Makey Makey kit to make and use a custom video game controller.

Light Challenges	Laser Defender	5	Learners use mirrors and lasers to create and test a laser “security system.”
Renewable Energy Challenges	Wind Commander	4	Learners experiment with using wind energy to power a turbine and complete various tasks.
	Solar Roller	3	Learners experiment with using solar energy to power a model car.
Sound Challenges	Ringtones	3	Learners use Soundation to mix tracks into custom ringtones.
Chemistry Challenges	Just Bead It	5	Learners explore principles of chemistry and biology by making bead “cells.”
Building Challenges	Spaghetti Structures	2	Learners race against the clock to build the tallest tower possible using limited amounts of spaghetti and marshmallows.
	Coaster Boss	3	Learners attempt to build the fastest roller coaster using foam and marbles.

Table 2

Cognitive Spatial Processes Identified as Part of Distributed Spatial Sensemaking

Category	**Definition**	**Cognitive Process**	**Definition**	**Example**
Intrinsic-Static	"Perceiving objects, paths, or spatial configurations amid distracting background information"	Disembedding	Distinguishing shapes or objects from distracting background information	"So that's this one1" 1*Student pulls capacitor wire out of bread board, then plugs it back in to a different hole shown in the instructional video.*
		Categorizing Space	Describing or labelling individual shapes or objects	"It looked like a triangle."
		Quantifying Space	Attaching numerical measurements, dimensions, or counts to objects	"119 inches, on this side" 1Measures height of spaghetti structure.

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"	2D to 3D Translation	Relating or translating between 2D and 3D representations	*Student draws a line down the center of the roof of her CAD model home, then pulls the line up, making a pointed roof on top of the structure*.
		Mental Rotation	Mentally representing and rotating 2D or 3D objects in space	"How do you like rotate it like to be…I want the couch to be facing the TV1" 1*(TV is currently perpendicular to couch.) Student holds hand up to CAD model on screen making grabbing gesture over couch, then moves hand forward into open*

		space in front of TV.
Mental Simulation	Visualizing dynamic motion of a static object or representation	"But if this gets to the same level, the thing will wrap over the this[1] and get stuck." [1]*Points to tape wad on back of wind turbine.*
Mental Folding	Spatial visualization involving the folding of 2D patterns or materials into 3D objects and representations	Student makes a triangle out of spaghetti, attached to a square she's already made. Then she folds the point of the triangle up and over and connects it to another corner of the square using

				another piece of spaghetti.
		Scaling or Scale Changes	Visualizing scale changes of objects	Student shrinks cylinder on her screen and places it inside the 3D letter she has just made.
Extrinsic-Static	“Understanding abstract spatial principles, such as horizontal invariance or verticality”	Spatial Relations	Visualizing or describing relations between objects or between self and objects	“It's right on top. It's right next to the big one.”
		Describing Relative Size	Similar to spatial relations but specifically about the relative size of objects (e.g., big, small, bigger, smaller), in other words, relative properties of objects versus relative location of objects	“You wanted the O taller than the other letters?”
Extrinsic-Dynamic	“Visualizing an environment	Perspective Taking	Updating static representations given self-movement	“[1]Ok, here's my son's room.[2]” [1]*Student orbits to a different view of*

in its entirety from a different position”			*his CAD model home. [2]Student zooms in on the room.*
	Dynamic Spatial Relations	Updating static representations given movement of objects	“It pushed that back.”

*Category definitions are drawn from Uttal et al. (2013, p. 4). List of cognitive processes and definitions are assembled from Harris, Newcombe, and Hirsh-Pasek (2013), Hegarty (2004), Newcombe & Shipley (2015), and Uttal et al. (2013). Examples are from our dataset.

Table 3

Resources Used During Distributed Spatial Sensemaking

Resource	**Example**
Other Students	Johanna: Victoria, how do you fix the holes again? Victoria: Like that.[1] Erase. [1]*Comes over and uses Johanna's mouse to draw a line through the hole in the wall of Johanna's CAD model home. The hole disappears.*
Adults in the Room (FUSE facilitator, researchers, and occasionally district STEM coordinator)	Jeff: Mr. Steve, um, like why would you have to make it solid for it to print? Steve: Uh, because the way the printer's software works, it needs, it slices[1] your project into, well you can sort of tell[2]. It slices your project into layers[3]. So it's got this sort of special software that will take and object and slice it into layers. [1]*Makes slicing gesture with hand* [2]*Walks over to printer* [3]*Makes horizontal slicing gesture*
Written Instructions on the FUSE Website	Reagan: 'kay, wait, so what do we have to do? Amadia: Uh, let me go read it again.[1] [1]Goes back to her computer to re-read the challenge directions.
Diagrams	Erin: [1]Alrighty, so we need to...so the solar panel's right here[2]. The motor's right here[3]. [1]*Turns back to computer and looks at solar roller diagram.* [2]*Puts solar panel in place*

	[3]*Puts motor in place*
Help Videos	Solar Roller Help Video: ...what we want to do is connect all the positive ends. So this is the positive end of the panel. It goes into the long leg row, which is the… Erin: [1]Ok, so the long leg. This is basically the long leg thing, so Ajay: So put it in the same exact row. [1]*Pauses help video.*
Tinkering with physical or digital materials	Adele: *Holds cube shaped spaghetti structure in two hands and wobbles it back and forth. Then attaches piece of spaghetti to top right corner of cube, on a diagonal, so that it extends down to table, bracing the structure.*
Sketches/Sketching	Adele: Ok, so let's plan it out first. Ok, so how are we gonna draw these things?[1] [1]*Picks up a piece of paper* AB: [1]Like a hexagon kinda shape? [1]*Reaches for the piece of paper and a pencil and draws a hexagon on paper*

Table 4

A Distributed Cognitive System Does the Last Level of the 3D You Challenge

Line	**Person**	**Talk**	**Actions**
1	Tia:	Okay.[1] Gosh,[2] how did you stay in this position?	*[1]Reaches across Kyle's body and takes Kinect from him without moving it. [2]Holds Kinect in place with right arm outstretched.*
2	Kyle:	[1]Now, James, you gotta move a little bit.	*[1]Walks around table and stands in front of computer, looking at computer screen.*
3	Kyle:	James!	
	James:	What?	
4	Kyle:	[1]Okay, move your chair.	*[1]Looks at the representation of James on the computer screen.*
5	James:		*Turns body and chair slowly.*
6	Kyle:	Okay, come over here a little bit[1]	*[1]Waves hand to the right.*
7	Tia:	Me?[1]	*[1]Begins moving to her right with the Kinect.*
8	Kyle:	No no no no[1] Now how do we get the top of his head? Because if you try to pick it up[2], it just says go back to last pose.	*[1]Holds hand out in "stop" gesture. [2]Lifts one hand up, then the other.*
9	James:		*Leans forward so they can scan the top of his head.*

10	Tia:	There we go. Now circle around holding your breath.	
11	Kyle:	Yeah, circle around.	
12	James:		*Begins to turn slowly.*
13	Kyle:	Ok, slowly, and wait. But this has to be[1] a little bit more.[2]	[1]*Waves hand to the right.* [2]*Points to representation of James' head on the computer screen, then waves hand to the left.*
14	Computer screen:		*Image of James' head rotates to side of screen so it looks like he's sitting on the wall.*
15	Tia:	[1]Whoa!	[1]*Laughs.*
16	Kyle:		*Laughs.*
17	James:		*Looks at screen and rotates his head slightly to align with the angle of his head on the screen.*
18	Tia:	What happened? Am I like[1]	[1]*Rotates Kinect back and forth but representation on screen stays the same.*
19	James:	[1]Ok, let's watch the video[2]	[1]*Gets up and points to the back or exit button on the screen.* [2]*Points to the screen again.*

Table 5

Adele Coordinates Spatial and Mathematical Thinking to Measure her Spaghetti Structure

Line	**Person**	**Talk**	**Actions**
1	Mr. Lewis:	That's really cool. So we ought to get that tape measure and take a picture of this, so when we finally get your account, we'll be able to	
2	Carmen:	$_1$It is...	*$_1$Holds measuring tape up to structure and measures height on a diagonal along side of pyramid structure.*
3	Mr. Lewis:	That's really cool.	
4	Adele:	I know!	
5	Carmen:	$_1$2 inches. It's 2 inches.	$_1$*Looks at wrong end of measuring tape*.
6	Adele:	Let me see it$_1$ = Ten$_2$ = ten = ten	$_1$*Reaches for tape measure, holds it up to structure, putting 0 end at top and measuring down, again on a diagonal. Instead of measuring whole height, she measures segments of spaghetti*. $_2$*Holds measuring tape up to different parts of structure, measuring pieces of spaghetti*.
7	Adele:		*Reconnects a piece of spaghetti that has come loose.*

8	Adele:	[1]Ok, 10, 10, 10 10 10.	[1]*Resumes measuring different parts of structure*.

Table 6

Adele Tries Different Approaches to Measuring her Spaghetti Structure

Line	Person	Talk	Actions
1	Adele:	[1]Hmm.[2] Miss [researcher's name], what do I do now?	[1]*Begins measuring pieces in centimeters, then stands back and looks at structure*. [2]*Looks around, then walks to researcher*.
2	Researcher:	Well, did you measure to see how tall it is?[1]	[1]*Walks to spaghetti structure with Adele*.
3	Adele:	Yes.	
4	Researcher:	How tall is it?	
5	Adele:	10 inches, then I got 4, then I kept getting 26's and 25's.	
6	Researcher:	So how 'bout the height? What would be the height of this?	
7	Adele:	10.	
8	Researcher:	So what would we measure on here to find the height?	
9	Adele:	The triangles?	
10	Researcher:	[1]So how would we find the total distance between the table[2] and this top part?[3]	[1]*Laughs*. [2]*Puts hand flat on table*. [3]*Researcher raises other hand up to top of structure*.
11	Adele:	U:::m.	

12	Researcher:	Is there a place where we could put that measuring tape to find that?	
13	Adele:	Right here?[1] Right there?	[1]*Points to outside of base of pyramid.*
14	Researcher:	M:::m, so we just want like from the table[1] to the top[2] right? So, what would that…	[1]*Puts hand on table.* [2]*Moves hand up to top of structure.*
15	Adele:	So from right here[1]	[1]*Points to base again.*
16	Researcher:	So what would that look like, if you measured from there?	
17	Adele:	So[1]	[1]*Holds measuring tape up to pyramid along diagonal side.*
18	Researcher:	Ok, so, yeah but look at, so see how you're also kind of measuring out this way too.[1] I wonder if there's a way we can prevent that?	[1]*Waves finger horizontally.*
19	Anna:		*Comes over toward Adele.*
20	Researcher:	I wonder if she has an idea.[1] How would she measure the height of this, to figure out how tall her marshmallow is?	[1]*Turns to Anna.*

21	Anna:	It's probably this side, or maybe this side[1]	[1]*Holds hands up to same diagonal where Adele had just proposed measuring*.
22	Anna:	Maybe start like right here[1] through here,[2] if that works, because the spaghetti, that's the straightest part.	[1]*Points to spot on table on other side of pyramid.* [2]*Raises hand up to marshmallow at top*.
23	Adele:	[1]19 inches, on this side[2] and on that side.[3]	[1]*Takes measuring tape and measures where Anna showed her, still on an angle*. [2]*Points to side she just measured*. [3]*Points to other side.*
24	Researcher:	Yeah? 19 inches, you agree with that?	
25	Anna:	Yeah.	

Table 7

Adele and Anna Coordinate Spatial and Mathematical Thinking to Measure Their Spaghetti Structure

Line	**Person**	**Talk**	**Actions**
1	Adele:		*Begins measuring but again does it on an angle up the diagonal side of the structure.*
2	Anna:	Ok, so how long is it?	
3	Adele:		*Measures only one leg of the tower, not the whole height.*
4	Anna:	No, measure it from this side. This is our tallest side.[1]	[1]*Points to top of tower on other side*.
5	Adele:	[1]7 inches.	[1]*Measures full height from top of tower, but still at a diagonal along side.*
6	Anna:	What? No[1]	[1]*Holds and looks at bottom of measuring tape on table*.
7	Mr. Lewis:	[1]So what you want to measure though is just from the marshmallow[2] to the ground, straight down.[3]	[1]*Comes over*. [2]*Points to large marshmallow on top*. [3]*Makes line with hand down to table.*
8	Adele:	Ok.	
9	Anna:		*Holds tape measure now, still along outside of tower, but on other side*.

10	Mr. Lewis:	So, you want zero to start at the top of the marshmallow and then go straight to the ground, right?	
11	Adele:	So, 10.	
12	Anna:	10.	
13	Mr. Lewis:	About 10 inches. Why do we not measure on the angle?[1]	[1]*Points to side of tower*.
14	Anna:	Because then you get a bigger measurement.	
15	Mr. Lewis:	Which would be great, right? But is it accurate?	
16	Anna:	But it's unfair.	
17	Adele:	No, no, no.	
18	Mr. Lewis:	Exactly. So are you going to try another one right now? See if you can try to build it higher? You still have about 15 minutes.	

Table 8

Erin, Ajay, and Aiden Wire a Capacitor into their Solar Car and Learn What it Does

Line	**Person**	**Talk**	**Actions**
1	Ajay:		*Shines light on solar car.*
2	Erin:	[1]Okay, okay, Aiden, we're going to have to set up the capacitators.	[1]*Goes back and looks at the directions.*
3	Erin:	Where's the bread board?[1] Oh here it is.[2] Which one? The big one. The big one. This one's the positive side.	[1]*Looks in the supply box.* [2]*Goes back to reading directions, sighs, then opens a diagram.*
4	Ajay and Aiden:		*Laughing.*
5	Erin:	What?[1]	[1]*Turns toward Ajay and Aiden.*
6	Ajay:		*Laughing.*
7	Erin:	What?	
8	Ajay:	He put his finger on the super glue thing.[1]	[1]*Holds up a plastic bag.*
9	Aiden:	I just picked it up, and it just gacked glue I guess.	
10	Ajay:		[1]*Starts rummaging through box.*
11	Erin:	Oh, I already got all the stuff.[1] Alrighty, so we need to...so the solar panel's right here.[2] The motor's right here.[3]	[1]*Turns back to computer with directions.* [2]*Puts panel in place.* [3]*Puts motor in place.*

12	Ajay:	Here, first…	
13	Erin:	No, stop stop stop stop!	
14	Ajay:	Start with the car. Then see what you can do with it.	
15	Erin:	No, don't:::oh then that, yeah.[1] Ok, so then we're going to have to put the negative side in one of these things[2] and the positive side[3]:::where the positive side:::and don't ask why I know which one's negative.	[1]*Looks at diagram on screen.* [2]*Inserts negative leg of capacitor into hole in breadboard.* [3]*Looks back up at diagram on screen.*
16	Ajay:	We should do like more research at our houses.	
17	Erin:	If I could fit this thing in here.[1] There I go. I'm just gonna add it. Ok so this is the capacitator, and it would, short leg on the capacitor.[2] Move the setup on the bread board. Wait what?	[1]*Inserts positive leg of capacitor into a different hole in breadboard.* [2]*Reads directions.*
18	Ajay:	What's a capacitator?	
19	Erin:	Um, it like gives energy, a short burst of energy, once the light disappears, continues the loop, but I don't get what[1] this is.	[1]*Points to diagram on screen.*
20	Erin:		Starts help video.

Table 9

Erin, Ajay, and Aiden Troubleshoot their Solar Car to Get it Across the Finish Line

Line	**Person**	**Talk**	**Actions**
1	Ajay:	[1]Why won't it work?	[1]*Shines light on solar car.*
2	Erin:	What did you do?[1]	[1]*Picks up car.*
3	Ajay:	I didn't do anything.	
4	Erin:	What did you do?	
5	Ajay:	Okay, hold on. Let me shift the motor. It should be able to[1]:::No the motor's too close.[2]	[1]*Takes car from Erin.* [2]*Repositions motor on car so that the gears engage with those on the wheel and shines light on it again. The wheels begin spinning in midair.*
6	Erin:	Okay, that's better. That's good.	
7	Aiden:	Wow, it's rolling.	
8	Ajay:	Okay	
9	Aiden:	That's good, but now	
10	Ajay:	Watch. Hold on.	
11	Aiden:	If you really do it, it goes like this.[1] Stop![2]	[1]*Moves hand quickly along carpet to edge of tunnel,*

			making engine sound. [2]*Stops hand.*
12	Ajay:	Hold on. Watch this. With this, the um, compactor, with the compactor, look how	
13	Ms. Vonn:	Did it go through yet?	
14	Erin, Ajay, and Aiden:	No	
15	Ms. Vonn:	Why not?	
16	Ajay:	[1]Look,[2] it's still running. It's good.	[1]*Switches off light.* [2]*Wheels are still spinning in midair.*
17	Erin:	Maybe it's the carpet? Maybe we should put paper on the bottom.[1] Or on a smoother surface?	[1]*Furrows eyebrows.*

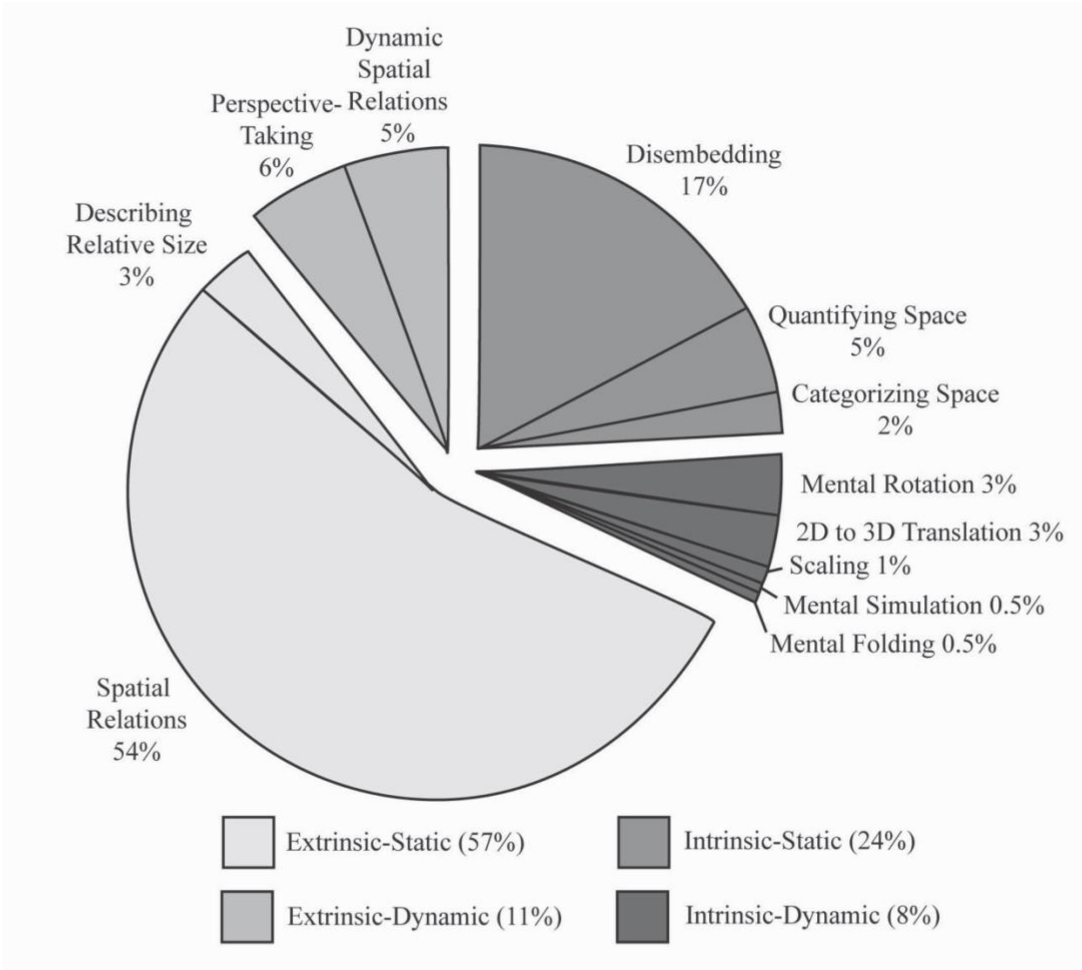


Figure 1. Spatial reasoning skills identified through qualitative categorical coding broken out by category.

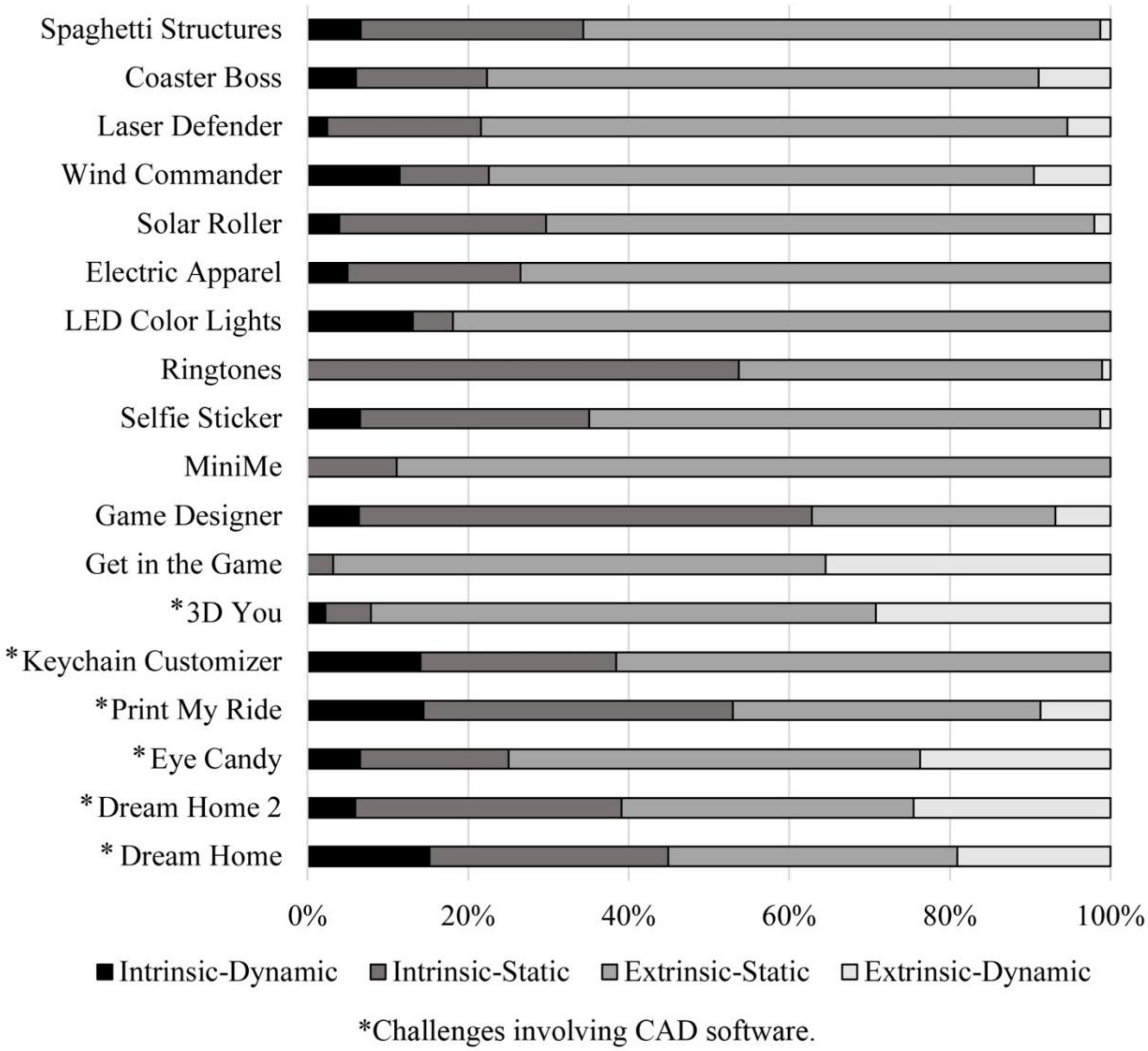


Figure 2. Types of spatial skills by challenge, as a percentage of total spatial idea units communicated through talk, gesture, or object manipulation during completion of that challenge.

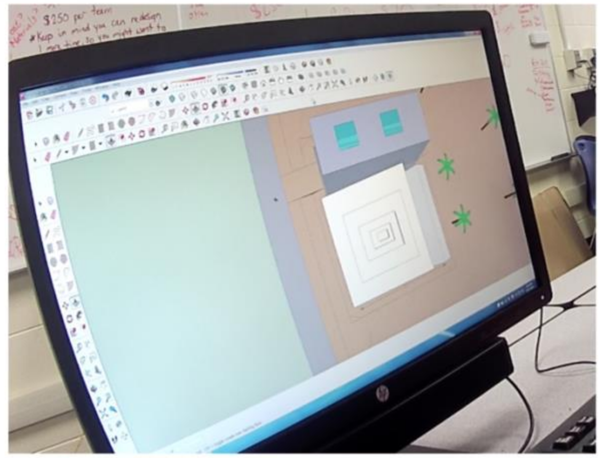
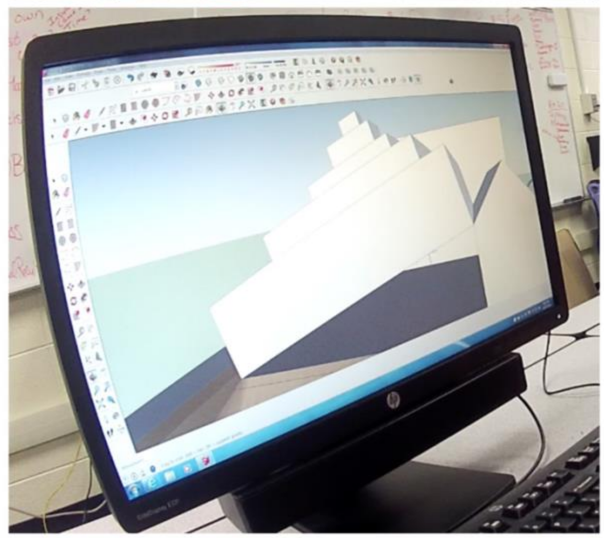
Line	Person	Talk	Actions	Representation on Screen
1	Johanna:		*Finishes making pyramid, while looking at CAD model home from above.*	
2	Johanna:	[1]Ah! Why is it slanted?!	[1]*Orbits around house so that she's looking at it from the side instead of above.*	
3	Researcher:		*Laughs*	
4	Johanna:	No:::o!		
5	Researcher:	Aww	*Laughs*	
6	Johanna:	I finally got something and it didn't work!		

Figure 3. Johanna mistakenly builds a structure on a diagonal rather than flat on the ground, because she didn't engage in perspective taking.

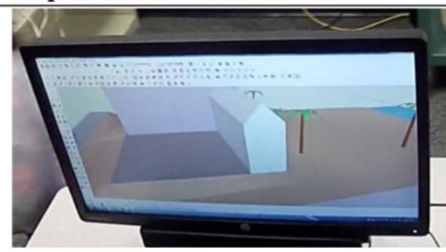
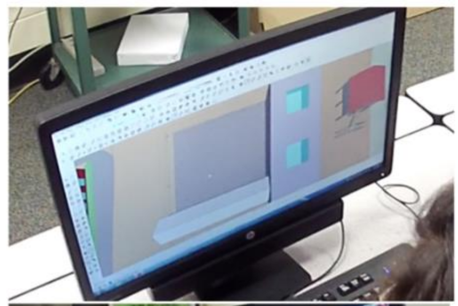
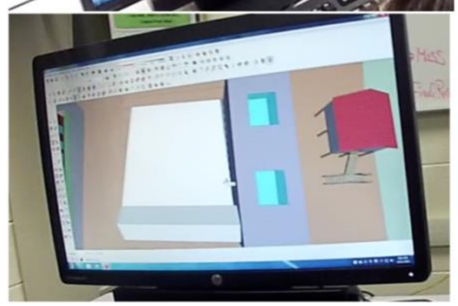
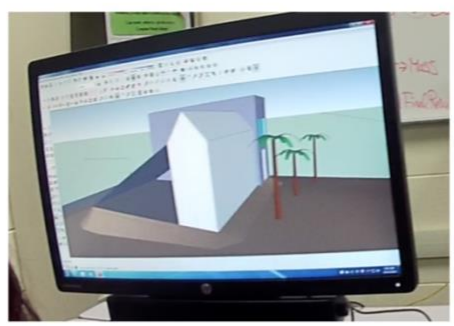
Line	Person	Talk	Actions	Representation on Screen
1	Johanna:	But how do I make that 3D slanted thing again?		
2	Researcher:	[1]Well how did you do it last time? I wasn't, I wasn't here for that last time. You did that all by yourself.	[1]*Laughs*	
3	Johanna:	[1]I want to make my strange looking hut.	[1]*Changes perspective on her house using the "orbit" tool.*	
4	Johanna:	[1]Oh! Yes![2]	[1]*Creates a square on an angle like she had it before.* [2]*Throws arms up in air.*	
5	Researcher:	Awesome! Yay!		
6	Johanna:		*Changes perspective using the "orbit" tool to view structure from the side.*	

Figure 4. Johanna begins to engage in perspective taking to recreate her slanted pyramid structure.

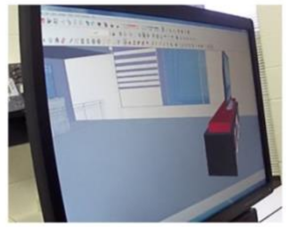
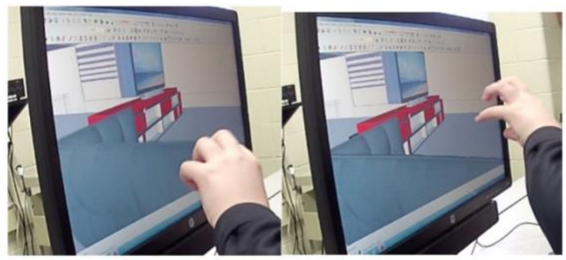
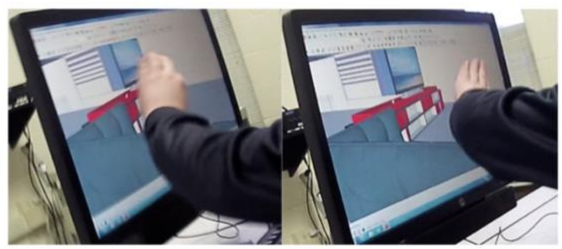
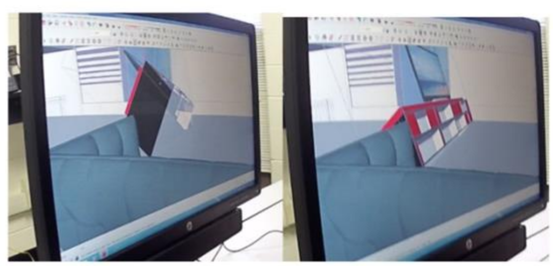
Line	Person	Talk	Actions	Representation on Screen
1	Evan:	How do you like rotate it like to be		
2	Victoria:	I don't know like		
3	Evan:	To for the couch or like the TV to be like,[1] I want the couch to be facing the TV	*[1]Zooms in and changes perspective. [2]Holds hand up to screen making grabbing gesture, then moves hand forward and turns it slightly.*	
4	Victoria:	Hmm.		
5	Evan:	Or I would, no I want the TV on the wall.[1]	*[1]Makes another grabbing gesture and moves hand across screen toward wall again.*	
6	Victoria:	Maybe, try this.[1]	*[1]Points to rotate tool icon on toolbar.*	
7	Evan:		*Smiles.*	
8	Victoria:	Maybe, I don't know.[1]	*[1]Laughs.*	
9	Evan:	[1]Woah! Wha?! What?! I'm scared. [2]	*[1]Selects rotate tool and rotates TV but rotates it around the wrong axis. [2]Rotates TV back to where it was initially.*	

Figure 5. Evan engages in mental rotation while designing a CAD model home.

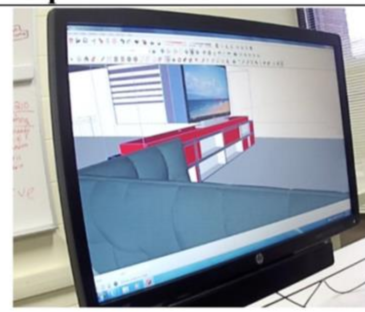
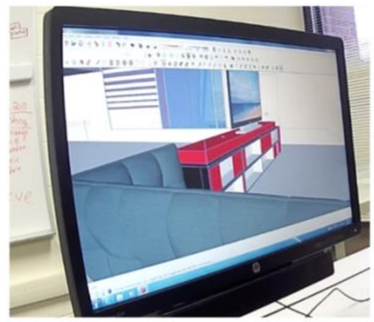
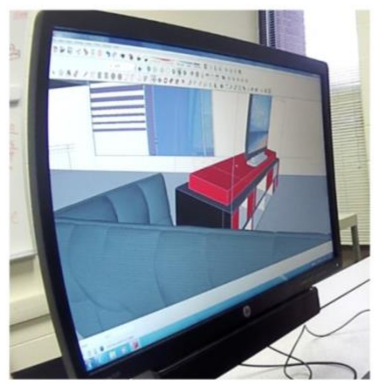
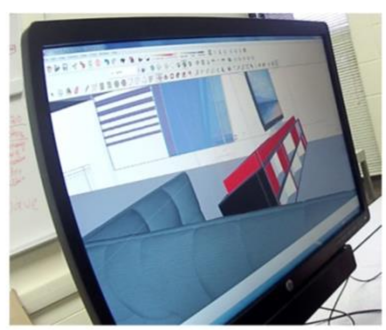
Line	Person	Talk	Actions	Representation on Screen
10	Evan:	I'm not doing that.		
11	Victoria:	Yeah. Oh those things!		
12	Evan:		*Moves TV forward.*	
13	Victoria:	Ah:::a. What about, is there another arrow thing?		
14	Evan:	Yeah[1]	[1]*Rotates TV backward and then back to its original position.*	
15	Evan:	[Ah! Help!		
16	Victoria:	[Nope, nope, no no.		
17	Evan:	Uh, yeah. Ah![1]	[1]*Rotates TV forward and then back to its original position.*	
18	Victoria:	Scroll		

Figure 6. Victoria helps Evan figure out how to rotate his TV around the right axis to get it across from his couch.

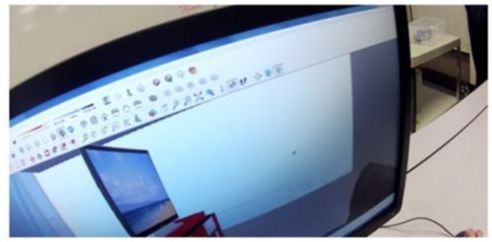
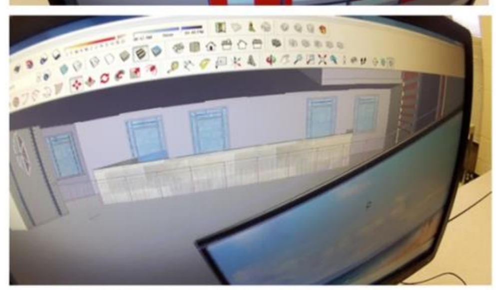
Line	Person	Talk	Actions	Representation on Screen
1	Victoria:	Hold on let me see.[1]	*[1]Takes Evan's mouse.*	
2	Evan:	This is so horrible. Please don't erase it.		
3	Victoria:	I won't. I'm looking around.[1] Ah! Where am I? Oh there.	*[1]Orbits around the room to look at TV from a different perspective.*	
4	Evan:	Uh let's see.[1]	*[1]Takes mouse back and moves TV backward and forward.*	
5	Victoria:	What is this one?[1] There[2]	*[1]Rotates TV sideways then quickly puts it back. [2]Goes back to her computer.*	
6	Evan:	[1]So scary.[2] Oh there we go.	*[1]Takes back his mouse and changes perspective. [2]Places rotate tool on a different axis and rotates TV against wall.*	

Figure 7. Victoria helps Evan figure out how to rotate his TV around the right axis to get it across from his couch.

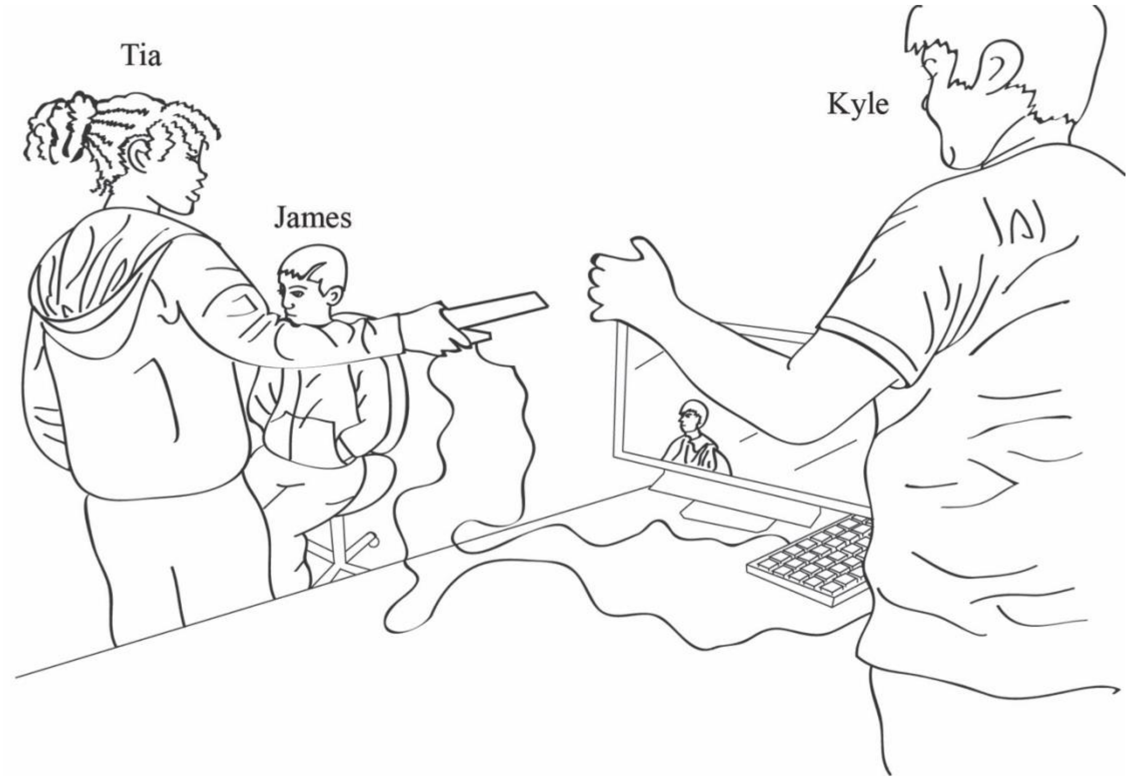


Figure 8. A distributed cognitive system does the last level of the *3D You* challenge.

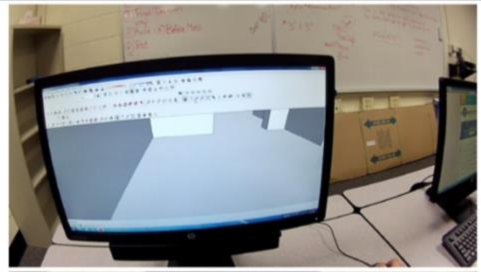
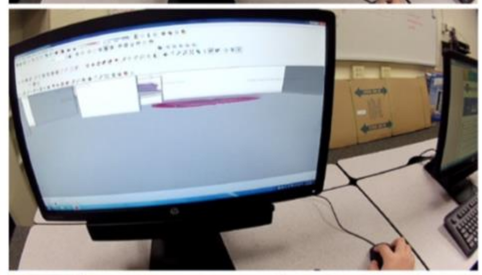
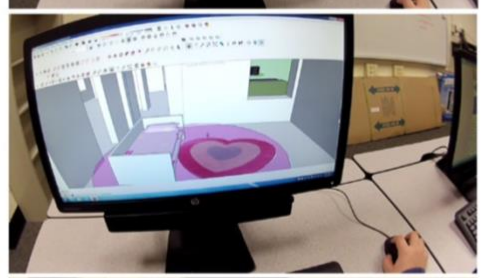
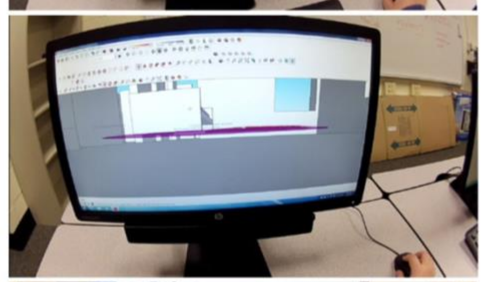
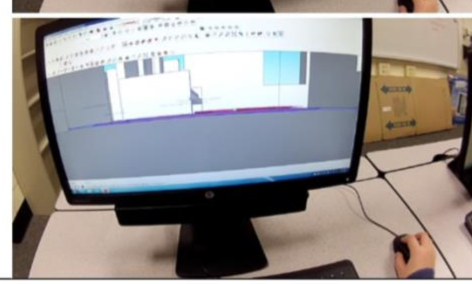
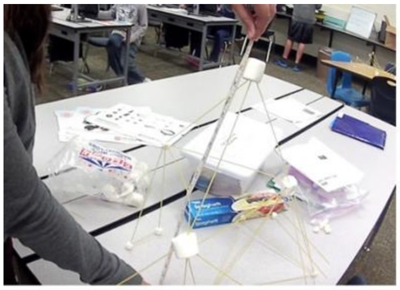
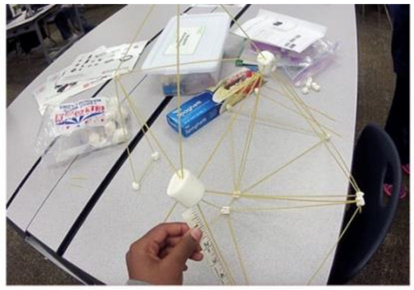
Line	Person	Talk	Actions	Representation on Screen
1	Johanna:	Victoria? Victoria, I forgot how to make them like go on the ground. Like it's always kind of[1]	[1]*Zooms in on dream home floor, then moves rug.*	
2	Johanna:	[1]Oh,[2] Victoria, I actually put it on the ground the first time!	[1]*Uses "orbit" tool to change view so side view of rug is visible.* [2]*Gasps.*	
3	Johanna:	[1]Wow.[2]	[1]*Orbits up and down.* [2]*Changes view to look at rug from above. Rug is now in the floor.*	
4	Johanna:		*Pulls rug up using the "move" tool.*	
5	Johanna:		*Orbits to side view again. Now the rug is floating in midair.*	
6	Johanna:		*Moves rug down until it's flat on the floor.*	

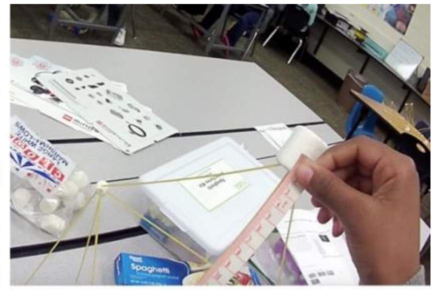
Figure 9. Johanna engages in perspective taking to place a rug on the floor of her model home.



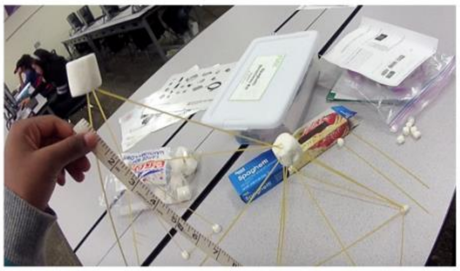
(a) Carmen reading the measuring tape incorrectly



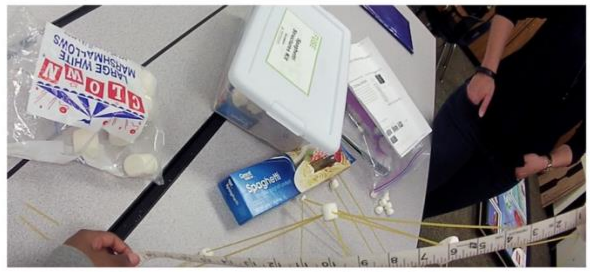
(b) Adele measuring individual pieces of spaghetti



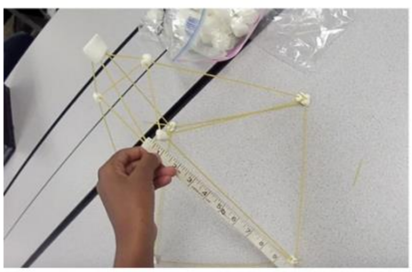
(c) Adele measuring individual pieces of spaghetti in centimeters



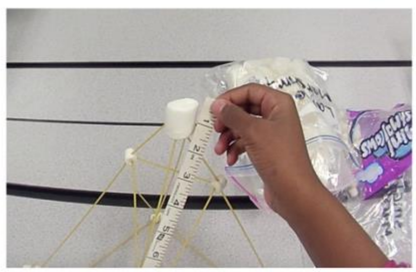
(d) Adele measuring whole height of structure on a diagonal



(e) Adele measuring whole height of structure on a diagonal up the other side



(f) Adele measuring individual pieces of spaghetti



(g) Adele measuring whole height of structure on a diagonal up the side

(h) Anna measuring along the other, straighter side

Figure 10. Adele, Carmen, and Anna's approaches to measuring their spaghetti structures develop over time.

(a) Chair tunnel (b) Paper tunnel (c) Box top tunnel

Figure 11. Erin, Ajay, and Aiden create different tunnel designs.

Appendix

Descriptive Statistics for Spatial Reasoning by Challenge

	Total Spatial Idea Units/Hour	**Intrinsic-Static Percent of Total Spatial Idea Units**	**Intrinsic-Dynamic Percent of Total Spatial Idea Units**	**Extrinsic-Static Percent of Total Spatial Idea Units**	**Extrinsic-Dynamic Percent of Total Spatial Idea Units**
Dream Home	*M* = 90.67	*M* = 8%	*M* = 13%	*M* = 45%	*M* = 19%
	SD = 52.8	*SD* = 8%	*SD* = 3%	*SD* = 17%	*SD* = 1%
Dream Home 2	*M* = 112.44	*M* = 22%	*M* = 5%	*M* = 32%	*M* = 21%
	SD = 45.87	*SD* = 17%	*SD* = 1%	*SD* = 6%	*SD* = 5%
Eye Candy	*M* = 50.67	*M* = 21%	*M* = 7%	*M* = 53%	*M* = 19%
	SD = 28.28	*SD* = 8%	*SD* = 2%	*SD* = 5%	*SD* = 15%
Print My Ride	*M* = 68.12	*M* = 29%	*M* = 18%	*M* = 41%	*M* = 12%
	SD = 71.82	*SD* = 16%	*SD* = 7%	*SD* = 4%	*SD* = 5%
Keychain Customizer	*M* = 17	*M* = 22%	*M* = 14%	*M* = 64%	*M* = 0%
	SD = 1.41	*SD* = 8%	*SD* = 2%	*SD* = 9%	*SD* = 0%
3D You	*M* = 59.33	*M* = 10%	*M* = 1%	*M* = 54%	*M* = 35%
	SD = 70.71	*SD* = 7%	*SD* = 2%	*SD* = 15%	*SD* = 10%
Coaster Boss	*M* = 293.14	*M* = 22%	*M* = 5%	*M* = 71%	*M* = 8%
	SD = 199.61	*SD* = 14%	*SD* = 4%	*SD* = 2%	*SD* = 4%

Spaghetti Structures	*M* = 199.5	*M* = 24%	*M* = 6%	*M* = 68%	*M* = 2%
	SD = 77.07	*SD* = 9%	*SD* = 2%	*SD* = 9%	*SD* = 2%
Electric Apparel	*M* = 136.67	*M* = 21%	*M* = 5%	*M* = 74%	*M* = 0%
	SD = 46.2	*SD* = 8%	*SD* = 0%	*SD* = 9%	*SD* = 0%
Solar Roller	*M* = 217.33	*M* = 19%	*M* = 3%	*M* = 73%	*M* = 5%
	SD = 148.02	*SD* = 17%	*SD* = 1%	*SD* = 12%	*SD* = 6%
Wind Commander	*M* = 220.96	*M* = 8%	*M* = 18%	*M* = 68%	*M* = 6%
	SD = 33.99	*SD* = 7%	*SD* = 13%	*SD* = 1%	*SD* = 7%
Laser Defender	*M* = 37.43	*M* = 20%	*M* = 3%	*M* = 73%	*M* = 5%
	SD = 15.89	*SD* = 5%	*SD* = 2%	*SD* = 2%	*SD* = 4%
MiniMe	*M* = 13.83	*M* = 9%	*M* = 0%	*M* = 91%	*M* = 0%
	SD = 12.49	*SD* = 12%	*SD* = 0%	*SD* = 12%	*SD* = 0%
Game Designer	*M* = 58.5	*M* = 51%	*M* = 10%	*M* = 33%	*M* = 6%
	SD = 27.58	*SD* = 22%	*SD* = 14%	*SD* = 11%	*SD* = 3%
Get in the Game	*M* = 194.67	*M* = 3%	*M* = 0%	*M* = 60%	*M* = 37%
	SD = 123.51	*SD* = 3%	*SD* = 0%	*SD* = 6%	*SD* = 9%
LED Color Lights	*M* = 41.5	*M* = 3%	*M* = 31%	*M* = 66%	*M* = 0%
	SD = 53.03	*SD* = 4%	*SD* = 26%	*SD* = 23%	*SD* = 0%
Ringtones	*M* = 153.49	*M* = 53%	*M* = 0%	*M* = 45%	*M* = 1%
	SD = 80.86	*SD* = 3%	*SD* = 0%	*SD* = 1%	*SD* = 2%
Selfie Sticker	*M* = 157.1	*M* = 30%	*M* = 10%	*M* = 59%	*M* = 1%
	SD = 82.17	*SD* = 3%	*SD* = 10%	*SD* = 14%	*SD* = 1%