STEAM Learning in an In-school Makerspace: The Role of Distributed Spatial Sensemaking

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Abstract: This study examines technology-enhanced STEAM learning among fifth and sixth grade students in one set of in-school makerspaces. It focuses on the learning of one set of meta-disciplinary skills, spatial skills. Prior research has shown these skills to be relevant for STEAM achievement, but they have been underemphasized in our schools and in the literature on learning through making. Informed by a distributed cognition perspective and using a combination of qualitative categorical coding and interaction analysis, this study provides a learning sciences approach to studying spatial thinking and learning. Analyses show that during making activities students engaged in frequent and diverse spatial thinking with a variety of social and material resources and that the sociomaterial contexts of different making activities facilitated different types of spatial thinking. They also show that spatial thinking developed over time and led to problem-solving insights.

Keywords: STEAM, makerspace, spatial thinking, interaction analysis, mixed methods

Makerspaces have become explosively popular in recent years. Many believe they hold promise as contexts for integrated STEAM (science, technology, engineering, arts, and math) learning, meta-disciplinary skill learning, and promoting interest and equity in STEAM (e.g., Blikstein, 2013; Hilton, 2010; Martin, 2015; Sheridan et al., 2014; Vossoughi & Bevan, 2014; Vossoughi et. al., 2013). However, we still know relatively little about what is actually learned in these spaces, how it is learned, and how to evaluate learning in ways that don't interfere with the informal structure of making activities. As makerspaces gain in popularity and move increasingly from informal contexts into schools, it is essential that we answer these questions.

This paper tackles these questions, using one particular set of skills, spatial skills, as an example. We've chosen to focus on this particular set of skills, because spatial skills predict performance in college STEAM courses (e.g., Hsi, Linn, & Bell, 1997; Sorby, 1999; Sorby, 2009; Sorby & Baartmans, 2000; Sorby, et al., 2013; Tseng & Yang, 2011) and entry into STEAM disciplines (e.g., Humphreys, Lubinski, & Yao, 1993; Lubinski, 2010; Shea, Lubinski, & Benbow, 2001; Wai, Lubinski, & Benbow, 2009). They also play a central role in the practices of STEAM professionals (e.g., Dogan & Nersessian, 2010; Stevens & Hall, 1998), and are often used in everyday thinking and learning (e.g., Hutchins, 1995; Scribner, 1984; Wagner, 1978). Further, contrary to the historically dominant notion that spatial skills are innate and fixed, recent research has demonstrated that these skills are learnable (Uttal et al., 2013) and thus can be improved through instruction or hands-on experience. However, traditional, textbook learning often de-emphasizes spatial thinking, in favor of verbal or analytic approaches to knowledge. As a result, spatial skills are systematically undervalued and underdeveloped in our schools (e.g., NRC, 2006; Newcombe, Uttal, & Sauter, 2013).

In contrast, hands-on, project-based, learning activities, like the ones found in makerspaces, have the potential to spatialize (Newcombe, et al., 2013) STEAM content, by situating learning within work with physical and digital objects and spatial representations, rather than limiting it to the verbal and analytic domains. In particular, the technological tools used in makerspaces, such as CAD (computer aided design) software and 3D printers, both require and have the potential to improve spatial skills (Basham & Kotrlik, 2008; Onyancha, Derov, & Kinsey, 2009; Shavalier, 2004; Sorby, et al., 2013). However, analysis of the development of these skills is conspicuously absent from the literature on learning in makerspaces. This leaves open questions regarding how or whether these skills are actually used or learned in these spaces and how they support other types of learning. This paper addresses these questions using data from an ethnographic study of middle school students engaged in STEAM learning activities in one set of technology-rich, in-school makerspaces.

Theoretical framework

We know relatively little about *how* spatial skills are learned and *how* they might support early STEAM learning, either in makerspaces or in other STEAM learning contexts. This is, in part, because the research that has been done on spatial thinking and learning has relied primarily upon psychometric assessments or laboratory experiments and *exogenous* rather than *endogenous* (Hall & Stevens, 2015; Stevens, 2010) accounts of learning.

Further, efforts at improving spatial thinking have focused on didactic, teacher (or experimenter) led instruction on specific, narrowly-constrained topics, rather than on ways to support student inquiry and problem-solving (e.g., Atit, et al., 2016; Congdon & Levine, 2017; Novack, et al., 2014; Stull & Hegarty, 2016).

In contrast, learning in makerspaces is more student- and inquiry-driven and spans a wide variety of tools and concepts. This necessitates a shift in focus away from didactic instructional approaches and standardized assessments and toward: (1) understanding the ways in which students spontaneously engage in spatial thinking and problem-solving, using a variety of social and material resources; and (2) designing activities that provide the right resources and task constraints to encourage particular types of spatial thinking.

To fill this gap, we draw on distributed theories of thinking and learning (e.g., Goodwin, 2000; Hutchins, 1995; Latour, 2005; Ramey & Uttal, 2017; Stevens & Hall, 1998) to frame our investigation of spatial thinking in makerspaces. Based on this theoretical framing, we conclude that spatial thinking should be examined within the sociomaterial context in which it is learned and applied. We also conclude that we should: (1) examine the specific interactions between people, tools, and representations through which spatial thinking is enacted and developed; and (2) trace specific spatial representations as they traverse across representational media, in order to understand how spatial understandings are distributed to or co-constructed by learners and their sociomaterial context. In doing so, we draw on the construct of *distributed spatial sensemaking*, or the idea that learners both employ cognitive spatial processes and draw on context- and activity-specific social and material resources to co-construct understandings of spatial phenomena (Ramey & Uttal, 2017). Here, we expand upon prior work by exploring: (1) the role that specific technological tools and activities available in makerspaces (e.g., CAD software, 3D printers, electronic circuits) play in facilitating specific types of spatial thinking; (2) how participation in making improves spatial thinking over time; and (3) the role that spatial thinking plays in supporting other forms of STEAM thinking and learning.

Method

The research presented here was conducted in one set of in-school makerspaces, FUSE Studios (Stevens et al., 2016). FUSE provides students with a set of integrated STEAM making and design challenges. These challenges are designed to be interest-driven, learner-centered, and inclusive of many different types of learners. There are almost 30 challenge sequences in which students complete challenge levels of increasing difficulty, according to their interests. Guidelines and resources for FUSE 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, such as Sketchup or Inkscape, housed on students' local computers, and physical tools and materials, such as 3D printers, circuit boards, or building materials, stored in individual FUSE studios.

The research presented here was conducted in five fifth and sixth grade classrooms, from one large, suburban, school district, with a relatively racially and socioeconomically diverse student population. Of the 127 students in the 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.

Drawing on cognitive ethnographic methods (Hutchins, 1995; Hollan, Hutchins, & Kirsh, 2000), we conducted ethnographic observations of classroom activity in five FUSE studios, one during the Spring of the 2014-15 academic year, and the other four during the entire 2015-16 academic year. For these observations, I, or another a member of the research team, attended every FUSE session (two per week for a total of 90 minutes), and collected field notes, video recordings, and pictures of artifacts. 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.

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 (at least two students or groups of students doing the challenge over one or more classes). For these 18 challenges, we selected for analysis two, contrasting cases of a student or group of students doing the challenge. We selected the first student case based on the amount and quality of available video, privileging cases where students worked most or all the way through the challenge. In selecting the second student 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 of the video data of that student doing the given challenge (anywhere between 30 min and fifteen hours of video per case).

In analyzing this data, we used a combination of qualitative categorical coding and interaction analysis. 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 coding talk, gesture, and object manipulation for evidence of cognitive spatial processes. Codes for cognitive spatial processes were derived from a recent taxonomy (Newcombe & Shipley, 2015; Uttal, et al., 2013), which compiles the diverse array of spatial skills identified in literature and divides them into intrinsic-static (e.g., disembedding), intrinsic-dynamic (e.g., mental rotation), extrinsic-static (e.g., locating an object or self with respect to a frame of reference), and extrinsic-dynamic (e.g., perspective taking). For the purposes of this study, we also revised this coding scheme, based on our observations of the types of spatial thinking students were engaging in. Drawing on prior work by Hutchins (1995), Goodwin (2000), and Stevens and Hall (1998), we also coded participants' idea units for both the human and non-human resources they were drawing on to aid in spatial sensemaking and problem-solving, including diagrams, instructional videos, written instructions, other students' descriptions (multimodal), instructors' descriptions (multimodal), and tinkering with or exploring materials. Then, we also analyzed *episodes* of distributed spatial sensemaking, using interaction analysis (e.g., Goodwin, 2000; Hall & Stevens, 2015; Jordan & Henderson, 1995; McDermott, Gospodinoff, & Aron, 1978; Mehan, 1982). We did this to better understand not just *what* cognitive processes and practices were being used, but *how* they were being used in interaction and what it was about the specific sociomaterial conditions and task constraints of the FUSE activities that led to their use.

Findings

Our analyses yielded four findings related to spatial thinking and STEAM learning in the context of FUSE activities. First, in making sense of and working through FUSE challenges, students engaged in frequent and diverse forms of spatial thinking and drew on a variety of both social and material resources, often in coordination with one another. Further, the different sociomaterial contexts and task constraints of different FUSE challenges facilitated different types of distributed spatial sensemaking. Over time, the spatial thinking occurring during different FUSE challenges developed, and finally, that spatial thinking led to STEAM problem-solving insights.

Students engaged in frequent and diverse spatial thinking with a variety of resources

Across all the data we analyzed of students working through FUSE challenges, we found 9393 instances of spatial thinking demonstrated through talk, gesture, or object manipulation. Students engaged in 13 different types of spatial thinking, spanning all four quadrants of the two by two taxonomy. The most commonly demonstrated were extrinsic-static skills (57 percent of total instances of spatial thinking), including thinking about spatial relations between objects or between self and objects (54 percent) and describing relative size (3 percent). These were followed by intrinsic-static skills (24 percent), including disembedding (17 percent), quantifying space (5 percent), and categorizing space (2 percent), then extrinsic-dynamic skills (11 percent), including perspective-taking (6 percent) and thinking about dynamic spatial relations between objects (5 percent), and finally intrinsic-dynamic skills (8 percent), including mental rotation (3 percent), 2D to 3D translation (3 percent), scaling or scale changes (1 percent), mental simulation (1 percent), and mental folding (less than 1 percent).

There are two things that are important to highlight in these findings. The first is the very large amount of spatial thinking going on during these activities (9393 instances). The second is the broad range of different spatial skills students demonstrated, and in particular, the relative infrequency of intrinsic-dynamic spatial thinking (8 percent or 713 instances), relative to other types of spatial thinking. This is important, because most of the psychometric tests used in correlational studies test primarily for these intrinsic-dynamic skills. So, by relying only on those, it's clear that we're missing a lot of what's going on in real-world problem-solving contexts.

Another important aspect of spatial thinking in real-world learning contexts that laboratory and correlational studies fail to account for is the heterogeneity of social and material resources that students draw on to make sense of spatial concepts and how the use of those resources shapes spatial thinking. In making sense of the spatial aspects of the various FUSE challenges, students used a variety of both social and material resources, often in coordination with one another. Social resources included both other students in the classroom (44 percent of total resources used) and the adults serving as FUSE facilitators (9 percent). Material resources included diagrams (3 percent), help videos (10 percent), and written instructions from the FUSE website (7 percent), physical or digital materials specific to challenges (28 percent), and sketches created by students (1 percent).

There are two things that are important to notice in these numbers. First is that many of the resources students drew upon, such as help videos, diagrams, sketches, and physical and digital materials had strong, inherently spatial components, whereas others, such as other students, facilitators, and written instructions, were not inherently spatial but were able to convey spatial information through practices such spatial language, gesture, and object manipulation. The second thing worth noticing is how infrequently students drew on the facilitator as a resource, relative to other resources available in the classroom. This contrasts with the structure of a traditional school classroom, where the teacher is the primary resource from whom knowledge is dispensed. This difference is important, as it emphasizes the need to move away from those traditional, didactic approaches to studying and improving spatial thinking and learning (or any thinking and learning) and toward looking at students' own spontaneous thinking and problem-solving with a variety of social and material resources.

Different challenges facilitated different types of spatial thinking

As one might expect, given the role that other people and material resources played in spatial thinking, the different sociomaterial contexts provided by different FUSE challenges led to different types of distributed spatial sensemaking. For example, Figure 1 shows the different spatial skills demonstrated during different challenges.

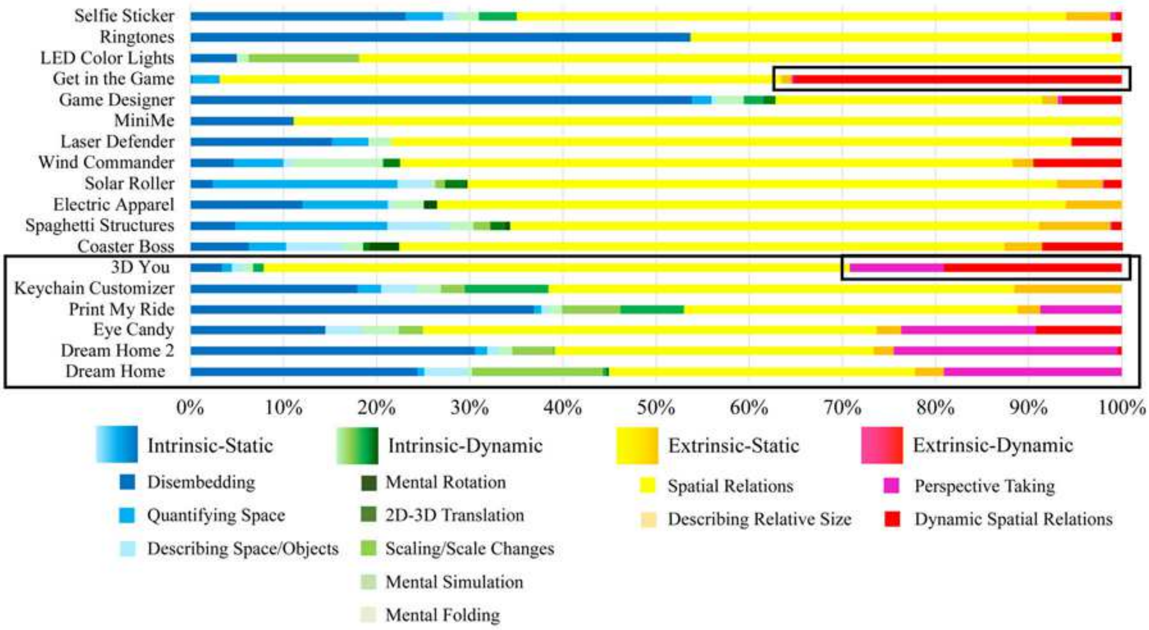

Figure 1. Spatial skills by challenge, as a percentage of total spatial idea units communicated through talk, gesture, or object manipulation during completion of that challenge.

There are two main things that are important to notice here. First is the relatively high frequency of both intrinsic-dynamic and extrinsic-dynamic spatial thinking 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 thinking. Second is the relatively high frequency of extrinsic-dynamic skills in challenges, such as *3D You* and *Get in the Game*. We argue that this is because these challenges required the coordinated movement of multiple people, physical and digital representations, and objects simultaneously, in order to complete the challenge.

Interaction analysis of episodes of distributed spatial sensemaking from these challenges demonstrates why this is the case. For example, the transcript in Table 1 shows an interaction between three students, Tia, Kyle, and James, as they worked together to do the last level of the 3D You challenge. The goal of this challenge level is to use a Kinect to scan a 3D image of one student's head (in this case James' head) into a software program, so that the student can 3D print a bust of himself. At the opening of the interaction, 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. So Kyle took on the role of monitoring the representation on the computer screen and instructing Tia and James movements in order to finish the scan.

In this excerpt, we can see that in order 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). Analysis of the human participants' contributions to this interaction shows that they engaged in a number of extrinsic-static and -dynamic types of spatial thinking, including perspective taking (lines 14-15, 24-25), and both static (line 6) and dynamic (lines 7, 10, 12, 14-19, 24-15) spatial relations. This episode demonstrates how an activity can be designed to encourage or necessitate the use of particular spatial skills. This contrasts with prior approaches to teaching spatial skills, which have involved didactic teacher-led instruction.

Table 1: A Distributed Cognitive System Does the Last Level of the 3D You Challenge

Line	Person	Talk	Actions
6	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))*
7	Kyle:	[1]Now, James, you gotta move a little bit.	[1]*((walks around table and stands in front of computer, looking at computer screen))*
8	Kyle:	James!	
9	James:	What?	
10	Kyle:	[1]Okay, move your chair.	[1]*((looks at the representation of James on the computer screen))*
11	James:		*((turns body and chair slowly))*
12	Kyle:	Okay, come over here a little bit[1]	[1]*((waves hand to the right))*
13	Tia:	Me?[1]	[1]*((begins moving to her right with the Kinect))*
14	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))*
15	James:		*((leans forward so they can scan the top of his head))*
16	Tia:	There we go. Now circle around holding your breath.	
17	Kyle:	Yeah, circle around.	
18	James:		*((begins to turn slowly))*
19	Kumar:	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))*
20	Computer screen:		*((Image of James' head rotates to side of screen so it looks like he's sitting on the wall.))*
21	Tia	[1]Whoa!	[1]*((laughs))*
22	Kyle:		*((laughs))*
23	James		*((looks at screen and rotates his head slightly to align with the angle of his head on the screen))*
24	Tia:	What happened? Am I like[1]	[1]*((rotates Kinect back and forth but representation on screen stays the same))*
25	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))*

Spatial thinking developed over time

Interaction analysis of spatial thinking during FUSE challenges also led to two important findings concerning learning. First, students' spatial thinking developed over time, through work on the FUSE challenges. For example, while working on the *Dream Home* challenge, one student, Johanna, tried to add an extra wing to her CAD model home. However, because when she created it, she was looking at her house from above, she accidentally created it on an angle, rather than flat on the ground. After initially getting frustrated, she decided that she liked the diagonal structure and turned it into a pyramid, which she used as a garage for her home. In fact, she liked it so much that, after accidentally closing her file without saving, she recreated it. In doing so, she was forced to employ perspective-taking to figure out how she had created it in the first place.

Then, in her later work on the *Dream Home 2: Gut Rehab* challenge, she demonstrated how her ability to engage in perspective taking in the CAD environment (Sketchup) had improved with experience. The illustrated transcript presented in Figure 2 shows how, after an initial plea for assistance from her friend, Victoria, she was able to independently and efficiently use the "orbit" and "pan" tools in Sketchup to select appropriate perspectives on her home to complete her desired task – placing a rug flat on the floor.

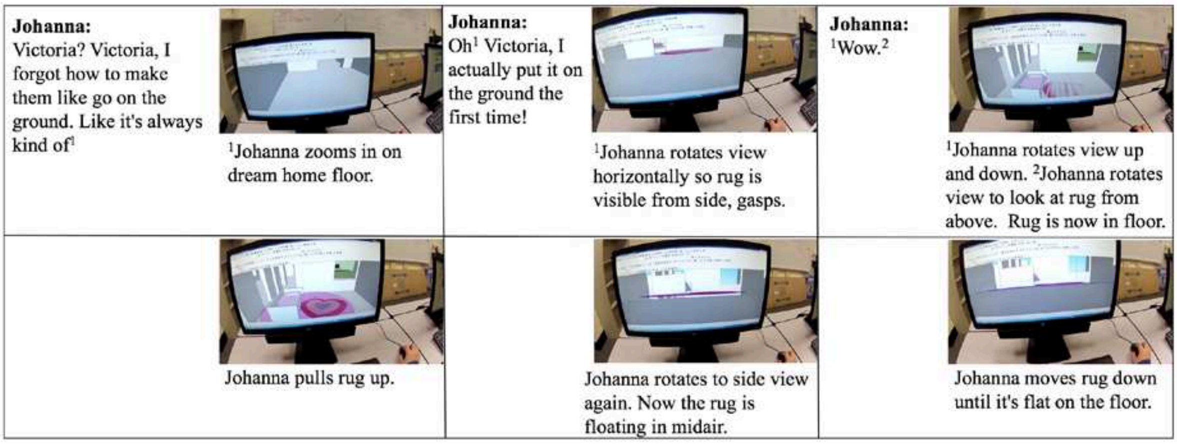

Figure 2. Johanna engages in perspective taking to place a rug on the floor of her model home.

Spatial thinking led to STEAM problem-solving insights

The other way in which distributed spatial sensemaking led to learning was by advancing problem-solving. For example, as one group of students worked through the *Solar Roller* challenge sequence, they encountered a number of problems, many of which were solved though spatial insights. For example, when they began Level 2 of the challenge (which requires that students create a 50-inch-long tunnel for their solar car to drive through), they searched for objects in the classroom that could be arranged into the shape of a tunnel. First, they used chairs, then printer paper, then box tops. Meanwhile, noticing that the wheels of their solar car were spinning faster in midair than on the carpet, they hypothesized that the car would go further or faster on a smooth surface. First, they tried pieces of paper on the carpet; then they moved to a smooth countertop. The students also integrated spatial thinking with mathematical thinking, calculating how many chairs, pieces of paper, or box tops they would need to create a 50-inch tunnel, and measuring the distance their solar car travelled on each run. Finally, throughout the challenge, the students engaged in multiple rounds of troubleshooting and iteration with the solar car itself, using help videos and diagrammatic instructions from the FUSE website or a combination of observations and tinkering to reconfigure their car, all of which involved spatial thinking.

Conclusions and implications

This analysis of learning in FUSE makes four main contributions. First, using spatial skills as an example, it provides a missing, close analysis of learning in makerspaces and thus provides a template for the systematic study of other types of thinking and learning during making activities.

Second, it shows *that* spatial thinking occurs in making activities, and *how* it both develops over time and advances problem-solving. As a result, the findings presented here improve our understanding of what is learned in makerspaces and how that learning happens. They also challenge traditional, psychological conceptions of spatial ability as individual, innate, and fixed. Finally, they provide both a missing account of the role of spatial thinking in early STEAM learning and an alternative set of methods for improving spatial skills.

Third, the prevalence of a wide variety of spatial skills and the frequent use of other people, tools, and representations shows what we're missing from only using psychometric assessments to study spatial thinking and learning. This finding emphasizes the importance of augmenting quantitative, exogenous accounts of spatial thinking and learning with qualitative, endogenous ones (Hall & Stevens, 2015; Stevens, 2010). This shift in methods may be particularly beneficial for capturing the spatial thinking and learning of female and low SES students, who underperform on psychometric assessments (e.g., Eliot & Fralley, 1976; Levine, Huttenlocher, Taylor, & Langrock, 1999; Levine, et al., 2005; Linn & Peterson, 1985) but may be capable of more when placed in more authentic problem-solving contexts and allowed access to relevant social and material resources.

Finally, this analysis shows how the different sociomaterial contexts and task constraints of different activities facilitate different types of distributed spatial sensemaking (e.g., intrinsic-dynamic spatial thinking with CAD software or extrinsic-dynamic spatial thinking in *3D You*). This provides an understanding of the types of tools, social arrangements, and activities that facilitate different types of spatial skills. As a result, this analysis can serve as a guideline for educators in selecting making activities to facilitate particular types of spatial skills. It also improves our understanding of the advantages of providing students with access to particular technology tools available in makerspaces, such as 3D printers and CAD software.

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