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Research Article

Exploring relationships between playspaces, pedagogy, and preschoolers' play-based science and engineering practices

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Abstract: This manuscript reports the results of a research study exploring the ways in which physical space and teacher pedagogy are related to preschoolers' engagement with science and engineering practices while at play. Using the Science and Engineering Practices Observation Protocol (SciEPOP), researchers captured children's engagement with the eight science and engineering practices identified in the Next Generation Science Standards (NGSS). This study explores relationships between specific playspaces, materials, and pedagogical strategies, and children's patterns of engagement with particular science and engineering practices during free play. There are notable differences in the spaces, materials, and pedagogies children encounter across the four participating preschools, and these differences suggest significant gaps in children's opportunities to engage in and deepen their enactment of science and engineering practices. The authors present evidence in support of adaptive, personalized strategies for deepening children's engagement with science through play, and raise questions about equity in early science learning environments that have implications both nationally and internationally for science education research, practice, and policy.

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Introduction

Children are natural scientists and engineers, exploring and manipulating the world around them (Cunningham, 2017; French, 2004; Gopnik, 2012; Greenfield et al., 2017; National Academies of Science, Engineering, and Medicine, 2021; National Research Council, 2007; Trundle, 2015; Trundle & Saçkes, 2012), and building understanding about that world through their interactions with others (Vygotsky, 1978). While children's play has long been recognized as critical to their learning and development (Akman & Özgül, 2015; Bonawitz, et al., 2011; Nayfield et al., 2011; Ross, 2013), little research has been done to document the ways that children engage in science learning through self-directed play. Instead, science in the early years is often conceptualized as necessarily directed by an adult and structured around a particular table or "station" in a classroom (Tu, 2006; Vitiello et al., 2019). This conception of early childhood science learning fails to account for the creative and intuitive ways that children engage with science as they interact freely with both indoor and outdoor playspaces. Even this teacher-directed science instruction is rare in early childhood education (Early et al., 2010; Piasta et al., 2014; Tu, 2006) and is particularly rare in classrooms serving low-income communities (National Research Council, 2007), specifically including Head Start settings in the United States (Gerde et al., 2018). This disparity in science engagement among low- and higher-income children leads to differences in science knowledge beginning as early as kindergarten, and it is a disparity from which lower income children rarely catch up (Morgan et al., 2016).

Though most states and nations have standards for primary and secondary science education, preschool educators often have little guidance around what science to teach or how to teach it. Add to this the persistence of low science self-efficacy and sparse science content background reported among early childhood educators (Barenthien et al., 2018; Gerde et al., 2018; Greenfield et al., 2009; Saçkes, 2014), along with a nearly ubiquitous focus on literacy and math in preschool curricula, and the result is often that

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preschool-aged children get little to no formal exposure to science. Further, the mere presence of science-related materials does not ensure children or teachers will engage with those materials through science and engineering practices (Fleer et al., 2014; Tu, 2006). In other words, the context (i,.e., playspaces and pedagogy) influences how children play.

This study addresses a significant gap in the literature around early years science learning by developing and using an instrument (the SciEPOP) to identify scientific and engineering practices in children's free play, characterizing those practices at multiple levels of sophistication, and accounting for pedagogical strategies or "teacher moves" that support or disrupt those engagements. In this manuscript, we offer empirical evidence that children at play are engaging with all NGSS-identified science and engineering practices (SEPs) at emergent and progressively sophisticated levels in a variety of school and care contexts. By focusing on playspaces that vary significantly in the types of materials, outdoor space, and access to the natural world available to children, we identify place-based elements that are associated with SEPs engagement. Further, we present an analysis of the pedagogical strategies that teachers use while children are engaged with these SEPs, paying particular attention to the patterns specific to strategies that facilitate or hinder play. Finally, we identify the implications of these findings for early childhood professional development, teacher practice, and research and evaluation purposes.

Science and Play

The role of play as a fundamental component of child development is recognized internationally (Gomes & Fleer, 2019; Howes & Smith 1995; Norðdahl & Jóhannesson, 2016; Pellegrini & Nathan, 2011; Weldemariam 2014). In fact, the *United Nations Rights of the Child*, article 31 explicitly states that play is the *right* of all children (1989), and the National Association for the Education of Young Children's (NAEYC) Code of Ethics (2005) explicitly states support for "children's development and learning; respecting individual differences; and helping children learn to live, play, and work cooperatively" (p.2). This central focus on collaboration and play in early childhood learning environments creates context for what Ross (2013) argues are "parallel processes in both individual and cultural learning"; but while play remains central to the curricula in many preschools, what little science learning happens in early childhood education (ECE) is often teacher-directed and structured around a particular table or "station" in a classroom (Tu, 2006; Vitiello et al., 2019).

This conception of early childhood science learning as a discrete activity happening at an assigned "station" fails to account for the rich experiences afforded when children interact freely with their natural environment. Further, some studies suggest that children's scientific process skills are better developed through exploratory and self-directed play than through direct instruction (Bonawitz et al., 2011; Bulunuz 2013). These early experiences with self-directed and collaborative science play may not only help children construct their own ideas about the natural world but may also help them develop a sense of agency and science identity (Barton & Tan, 2009; Barton et al., 2013; Cunningham & Carlsen, 2014), factors related to persistence in the study of science and engineering.

The release of the Next Generation Science Standards (NGSS) in the United States, a standards-based reform effort, has renewed focus on fostering science learning in early childhood and has given researchers and educators language with which to articulate children's engagement with science during play. The NGSS includes three critical and interdependent "dimensions" of learning: Science and Engineering Practices, Core Disciplinary Ideas, and Crosscutting Concepts (NGSS Lead States, 2013). This shift towards three-dimensional science learning emphasizes "figuring out", by engaging with science and engineering practices to explore phenomena, versus simply "learning about" what is already known (Schwarz et al., 2017). This approach to building science knowledge by "doing" the work of scientists and engineers (Lachapelle et al., 2013) has the potential to mitigate some of the historical tensions between the more individual, cognitively-focused goals of science education and the "whole child" approach of early childhood education that places equal emphasis on cognitive, affective, and social learning goals (Larimore, 2020).

This shift is laudable; however, existing observation protocols do not adequately capture the variety and depth of children's engagement with SEPs in play-based learning environments. In response to this need, the authors developed and validated the Science and Engineering Practices Observation Protocol (SciEPOP) - a tool benchmarked to the NGSS Science and Engineering Practices (2013) (Appendix F) and designed to support teachers, administrators, and researchers in the characterization of these practices in early childhood. The SciEPOP allowed researchers to explore a critical research question: How are early learning playspaces and teacher pedagogy associated with preschoolers' developing science and engineering practices in play-based learning?

Method

Instrument Development

The SciEPOP was developed in response to a clear need in this field for student-centered observation instruments. Existing tools focus primarily on teacher practices and do not account for children's science practices in these interactions. Early years observation tools including the Preschool Teacher Verbal Interaction Coding Form (Tu & Hsiao, 2008) and the Systematic Characterization of Inquiry Instruction in Early LearNing Classroom Environments (SCIIENCE)(Kaderavek, et al., 2015) focus on teachers and not the role of children and children's play in the teaching and learning. Tools at the elementary level such as the Reformed Teaching Observation Protocol (RTOP) (Piburn & Sawada, 2000; Sawada, et al., 2002), the Inquiry Science Observation Coding Sheet (Brandon et al., 2008), and the Practices of Science Inquiry Observation Protocol (P-SOP) (Forbes et al., 2013) have similar purposes.

In response to this lack of validated instruments for observing children's engagement with SEPs, Miller & Saenz (2019) developed the SciEPOP through an exploratory pilot study and an instrument validation study. The SciEPOP was developed and validated (Saenz & Miller, in process) using pilot data and classroom observations from one of the four preschools participating in a larger ongoing research project. Initial development and revision of the instrument was based on more than 20 hours of observations, as well as the aforementioned review of existing instruments, and literature rooted in early childhood education, play-based learning and science and engineering practices. This pilot study resulted in rich textual descriptions of children's engagement with various practices of science. Still images (digital photographs) were used as additional evidence to support textual descriptions.

The SciEPOP was designed with three distinct observational targets: science and engineering practices, pedagogical strategies, and playspaces and materials. We discuss each target briefly below.

The instrument requires trained observers to identify specific incidents during which children are engaging in one of the eight NGSS-aligned Science and Engineering Practices (Appendix F) (NGSS Lead States, 2013). Included in both the paper and app-based formats of the SciEPOP are brief descriptions and examples of each practice, allowing observers to make evidence-based decisions quickly. Practice 1 (Asking Questions) and Practice 8 (Obtaining, Evaluating, and Communicating Information) were coded separately because researchers were not able to determine *a priori* categories that aligned with the ordered hierarchies established for Practices 2 – 7. One of the guiding principles underlying the NGSS-outline practices is that students will make consistent progress in the complexity and sophistication with which they engage in SEPs; this progression is specified in successive grade bands. Likewise, the SciEPOP was developed with the understanding that children's engagement with SEPs will vary in complexity within and among individuals, sites, and over time. Therefore, the instrument allows observers to note the proficiency with which children engage in such practices, on an ordinal scale from "Emergent" (Level C) to "Proficient" (Level B) to "Exemplary" (Level A). These categorical descriptions, as discussed above, are informed by both pilot study data and prior work related to learning progressions and science practices (e.g., Berland & Reiser, 2008; Duschl & Bybee, 2014; Gotwals & Songer, 2013; Lehrer & Schauble, 2015; Schwarz et al., 2009), as well as the NGSS grade band expectations (Appendix F) (NGSS Lead States, 2013). For each SEPs, Level A engagement is specifically tied to at least one of the NGSS K-2 grade band expectations. Levels B and C may also be tied to NGSS K-2 grade band expectations and outline the progressive developmental steps toward Level A. For an example of how these codes are described and assigned using the SciEPOP, see Table 1 below.

Table 1. Excerpt from SciEPOP practice 2: developing and using models

Practice 2	Level A (Exemplary)	Level B (Proficient)	Level C (Emergent)
Developing and Using Models	• Develop or use a model to predict or explain something about the natural or designed world • Evaluate or revise the model (as when children add new components – branches, bark, roots – to their "castle" or "house" or indicate revisions – e.g. "This gate needs a lock" as they modify it)	• Compare model to the referent in the natural or designed world (identify common features and differences, i.e. correspondences and non-correspondences) • Develop a simple model based on evidence to represent a proposed object or tool (this includes physical models, 2D drawings or representations, and embodied models when children "pretend to be" something)	• Use physical replica as directed (by a teacher – e.g. "flip over your buckets and sit down in your boats"!) or intended (e.g. toy car; puzzles) • Distinguish between a model and the actual object, process, and/or events model represents

Pedagogical strategies - the behaviors of teachers as they interact with children engaging in SEPs - are a second key component of the SciEPOP and this study. The instrument allows observers to note any of seven pedagogical strategies: scaffolding, modeling, asking questions, direct instruction, disruption of play, mediating conflict, and safety concerns. As noted in more detail in our Results section, we grouped these strategies into two groups for analysis: management (actions that hinder play) and facilitation (actions that facilitate play).

Finally, the instrument allows observers to note details about the physical space and environment in which the observation takes place. This includes information about the materials and toys available to children (i.e. shovels, toy cars, water tables, play structures) as well as the "natureness" of the environment (i.e. presence of trees, dirt piles, wildlife, etc) (Sobel, 2015). While these factors are not individually analyzed in the present study, they offer a rich descriptive context for analyzing specific incidents as well as potential for future analyses. In our analysis, we use site profiles as proxies for physical space; each site offers a unique environment, characterized by indoor and outdoor space, access to nature and wildlife, and materials available to children during playtime.

The SciEPOP has two overarching purposes for use in the field. First, the instrument allows researchers to identify and categorize classroom-level engagements with science and engineering practices that support STEM learning. Second, the instrument provides data on "supporting characters" – the physical environment and materials as well as the educators' roles in the space. Together, these data allow researchers to describe and make claims about the integrated relationship among play, STEM, and early childhood environments. Our instrument development study (Saenz & Miller, in process) provides sufficient evidence to suggest that the SciEPOP successfully captures a wide range of levels and experiences across all eight practices, as well as critical information about physical space and pedagogy.

Methodology & Participants

This mixed methods study uses an exploratory sequential design (Creswell et. al., 2003) conducted over one year to account for seasonal changes in children's learning environments. Data were collected at four preschools in the Northeastern United States. The preschools were located in four different towns to capture a variety of demographics among participants including varying levels of rurality, income, and racial diversity. Three sites are Head Start programs, accounting for a range of families' socioeconomic backgrounds; two of those sites are associated with the same national nonprofit organization, another site is associated with a national nonprofit organization established with foundation support, and one site is associated with a liberal arts college, primarily serving families of faculty and staff at that institution (Table 2).

Site A is a nature- and play-based preschool, prioritizing self-directed play and eschewing plastic toys in favor of natural materials, "loose parts" (Nicholson, 1971) and outdoor spaces. Site B is a well-resourced, academic-focused, play-based preschool with ample space and materials for play but with a high degree of structure and teacher-directed activity. Site C is an under-resourced preschool which researchers characterize as "childcare-focused" and traditional in terms of spaces, materials, and schedule. Site D is moderately resourced, traditionally structured, and strikes a balance of childcare-focused and academic-focused. Full site profiles appear in the section below.

Table 2. Participating site demographics

Site	Enrollment	**Low income**	White	African/AfAm	Hispanic/ Latino	East Asian & Pacific Islander	Multiracial
A	46	0.0%	91.3%	0.0%	6.5%	0.0%	2.2%
B	208	76.0%	91.8%	0.0%	0.0%	1.9%	6.3%
C	63	28.6%	81.0%	6.3%	3.2%	3.2%	6.3%
D	60	10.0%	91.7%	0.0%	0.0%	1.7%	6.7%

Note: % of low income students is determined by % of Head Start eligible students.

Researchers did not individually identify participants for this project as the focus was on children's engagement with science and engineering practices during play rather than on individuals. Additionally, enrollment of students at three of the four preschools fluctuated over the course of the school year with some children leaving the schools and others joining preschool classrooms in between the four rounds of data collection. We provide greater context around demographics, teacher credentials, and curricular and pedagogical approaches in the site profiles that follow.

Site A Profile. The Site A preschool is housed in a childcare center associated with a college. The center has capacity for approximately 46 children from infancy through preschool. Of the teachers employed full-time at the center, 56% of them held master's degrees in ECE, including all three preschool teachers. The other 46% held bachelor's degrees. Site A was characterized as both nature-based and play-based with a strong leaning towards an attachment-based theory of care. Drawing from Reggio-Emilia and Waldorf-inspired approaches, the center website offers that "learning occurs when deeply attached relationships with adults and uninterrupted play exist". The preschool environment offers natural materials and "loose parts" (Nicholson, 1971) for children to use in their play. This reflects the philosophy of play that play materials should not dictate play, but rather familiar objects and materials (e.g. stones, fabrics, stumps, pillows, blocks) should be reflective of objects the child encounters in everyday life and should inspire rich and imaginative play (Olsen & Smith, 2017; Sutton, 2011). Further, the outdoor play yard could be characterized as a natural playspace, including stumps, sticks, dirt pathways, sand piles, climbing structures made from natural materials, and ample trees and shrubs to play among. While buckets, shovels, rakes, pans and scoops were readily available to children in the playspace, notably absent were any plastic toys.

Site B profile. The Site B preschool is part of a national nonprofit organization which aims to support young children from disadvantaged communities towards academic, social, and emotional readiness for school. The organization describes the four core features of their model as: data utilization, embedded professional development, high-quality teaching practices and intensive family engagement. The preschool is situated within a program that serves children and their families from infancy through preschool. The total program enrollment was 208, with 115 of those children enrolled in Head Start and 43 in Early Head Start. More than 75% of children at Site B qualify for FRL. Of the full-time lead teachers, 4% held a doctorate, 14% held master's degrees in ECE, 57% held bachelor's degrees, and 3% were enrolled in bachelor's degree programs. The Site B website touts a continuity of care and wrap-around service model, emphasizing "trust and relationship building" as well as "child-directed play". They use a published preschool curriculum which emphasizes literacy and social-emotional development. The preschool classrooms observed were highly structured and academically focused. Classrooms were divided into areas or stations for various types of play and learning. These included areas for blocks, sensory tables, art, reading, and dramatic play.

Children were encouraged to write their names on small whiteboards which hung at each area or station while they were playing there. This appeared to be a way for teachers to manage how many children were in any one area at a time and popular stations (such as the sensory table) often had a waitlist of children's names on the white board. The outdoor playspaces for preschoolers were described as natural playspaces and were divided into two large areas with a fence running in between. The outdoor spaces were constructed with a combination of natural elements (log-edged pathways, berms, shrubs and small trees) and man-made structures like slides, paved walking paths, synthetic turf, playhouses, and swings. Buckets, shovels, balls, and other toys were sometimes made available in the play yard but not always. Classrooms contained a traditional array of dolls, dress up clothes, Legos and other building materials, as well as plastic play food, books, and art supplies.

Site C profile: The Site C preschool is affiliated with a National nonprofit organization committed to "youth development, healthy living, and social responsibility". Site C enrolled a total of 63 children from infancy through preschool. Of those children, more than 50% qualified for FRL and 14% of those children were living in foster care. Of the nine full-time teachers at Site C, 11% held bachelor's degrees, 22% were enrolled in bachelor's degree programs, 22% held associate degrees, 11% were enrolled in associate degree programs, and 33% held no degrees. When asked about the program's theory of care, the director responded that they "create a safe and healthy living space for all children from all walks of life to thrive and grow at their own pace". This aligned with the program website which states that, "Our goal is to provide children with a safe and healthy learning environment that stimulates physical, social, emotional, and intellectual growth". Notably, the language of the program website emphasizes "childcare". This stands in direct contrast with Site A which emphasized language around play and secure, attached relationships and Site B which emphasized language around play and academic "readiness". Site C was located in a large, multiuse building in an urban area. Indoor classroom spaces (one for preschool-aged children and one for pre-K) were divided into areas or stations including blocks, dramatic play, movement, sensory table, reading, and several tables for teacher-led activities. The reading area in the pre-K classroom included a rocking chair and a carpet on which children could sit. The Site C indoor spaces included a traditional array of dolls, blocks, plastic play food, cars, trucks and figurines (e.g. dinosaurs, animals) and a plastic castle climbing structure with slide. Play areas were considerably more cluttered with toys and materials than at any of the other three sites. Children were permitted to use certain areas during free play and were prohibited from other areas by teachers.

The outdoor space at Site C was the smallest and most restricted of the four sites. The play yard was a narrow (approximately 5 meters across), fenced area that ran along the length of the building (approximately 20 meters). The play yard was covered in wood chips and had two climbing structures, one with sliding boards, in the center. At one end of the play yard was a staircase up to the main building where the classrooms were housed and at the other end of the play yard was a small plastic playhouse and a stationary metal rocking play structure shaped like an airplane. During the summer months a small water table was brought outside and sometimes filled.

Site D profile. The Site D program is affiliated with the same national nonprofit organization as Site C, though unlike Site C which is housed in a multiuse building, the Site D program is housed in a stand-alone building dedicated to childcare. The website of Site D articulated the same theory of care, stating "Our goal is to provide children with a safe and healthy learning environment that stimulates physical, social, emotional, and intellectual growth". Of the fourteen full-time teachers at Site D, 14% held bachelor's degrees and 21% were enrolled in bachelor's degree programs, 29% held associate degrees, and 36% held no degrees. The program focus appeared to be a combination of childcare and academic readiness, with more focus on the latter than researchers found at its sister site (Site C). Researchers noted that a significant number of families using that program were professionals employed by an adjacent college or by the hospital just down the street. Classroom spaces in Site D were more similar to those at Site B than at Site C. Rooms were neatly arranged into areas and stations including blocks, sensory tables, reading, dramatic play, and tables for art or other teacher-led activities. A traditional array of toys and materials were neatly arranged on shelving units that also delineated different areas for play and at Site D children were encouraged to take a small, laminated photo of themselves off of the wall and place it on a holder at the station they intended to play at during "free play" time. This appeared to be a way of managing how many children could play in one area or station at a time. Children were frequently reminded that they needed to find another area to play in if they entered an area where the determined limit of children had already been reached.

Site D had a large outdoor playspace with multiple large mature trees providing shade. In the center of the play yard was a very large climbing structure with multiple levels, slides and stairs. There was also a structure that appeared to have once had swings, but those had been removed. Around the playspace were several other structures, some movable (like a small plastic playhouse and picnic table) and some stationary, like a metal rocking structure. Central to the outdoor space was a very large tree along a sloping section of the yard. On the downhill slope, the tree roots were partially exposed, and children were frequently found digging, playing, and just sitting among those roots. For reasons not explained to the researchers, the side of the play yard to the other side of that large tree was off limits for the children and a spool of pink tape had been wrapped around the tree and draped along the yard between the large tree and another smaller tree. Children were reminded to stay on the near side of that tape line if they strayed under it. There were very few toys or materials brought onto the play yard relative to the number of children playing there. There were some trucks and cars as well as occasional tubs, shovels, and buckets. During the summer months researchers observed children playing with tubs of water and paint brushes (brushing water on the brick wall of the building and "washing off" the chalk art they had created there). Additionally, a sprinkler was brought out onto the play yard occasionally on hot summer days. The playspace at Site D was uniquely divided into the area of the large climbing structure, which seemed to host running, climbing, and generally loud, energetic play, and the large tree on the slope of the yard which appeared to attract more quiet play and rest among children.

Data Sources and Analysis

Researchers spent one year observing and recording children engaged in "free play", gathering more than 120 hours of video data across four preschools; at least eight hours of observation occurred at each of the sites during each of four seasons for a total of more than 30 hours of data per site over the year. Data were collected at four different times over the course of one year to account for seasonal changes in the play environment. Data were subsequently coded and analyzed using NVivo software. Data collected in this study suggest that the SciEPOP instrument allows trained observers to accurately and reliably capture and discriminate among all eight of the SEPs identified in the NGSS, as well as capture critical information about physical space, materials, and pedagogy.

Video data were then analyzed in NVivo using an *a priori* coding scheme developed to align with the SciEPOP. Coding was done at the grain size of complete instances or vignettes where students engaged with one or more practices during play. For each of these engagements the video was coded for each practice at Level A (Exemplary), B (Proficient), C (Emergent), or D (Not Present) along with notes related to "physical space" and "pedagogy".

A Note on Site Selection and Comparisons

Given that "playspace" is a key variable in our research questions and analysis, it is important to articulate how it is operationalized in this study. Selection of the four sites profiled above was an intentional decision and significant for the results and discussion that follow. Learning environments are complex systems in which children's development is shaped by the intertwining of their prior knowledge and background, relationships with peers and adults, interests, physical space, available materials, and more. There exist as many *types* of learning environments as there are sites, though some sites share significantly more elements in common. We use individual site contexts as proxies for playspaces, necessitating a rich description of each site and a nuanced examination of how each site's environmental context may reveal important underlying patterns related to space and pedagogy.

Some patterns in our analysis of science and engineering practices across the four sites (for example, the finding of higher frequencies of Level A practices at Site A, which serves a population of children of parents with typically high levels of educational attainment) might be dismissed by attributing them to selection bias. However, in order to make this argument, one must assert that some children are more capable of engaging in scientific inquiry than others, and that this proclivity is explained entirely by one's family background and not by the learning environment or by the pedagogy teachers engage with when interacting with students. We believe that this interpretation is short-sighted and runs counter to the pursuit of establishing more equitable learning environments for all children. We have intentionally selected sites for research that exhibit overlaps as well as differences. For example, both Site A and Site D serve families that work at colleges or other professional institutions. Sites B and D share similar physical spaces and materials inside and outside of the classroom. Finally, Sites A and B are similarly well-resourced and staffed with qualified EC educators, though the populations they serve are quite different. We have attempted to contextualize the four sites so that the emergent patterns around children's engagement with science and engineering practices in play, and the pedagogical supports that support or inhibit those engagements take on the significance they deserve.

Results

In this section, we present the results of our multi-stage analysis, beginning with overall patterns of children's engagement with science and engineering practices. We then break these patterns down by site and by practice level. In the second stage, we present findings specific to teacher pedagogy, overall and specific to site and level.

Science and Engineering Practices in Play

Our observations captured all eight practices at our four sites, though these practices were not evenly distributed. Practices 1, 2, and 3 were most frequent (4.8, 5.4, and 4.2 codes per hour, respectively). Practice 4 was observed 2.2 times per hour, and Practice 6 was observed 1.2 times per hour; Practices 5, 7, and 8 were the least frequently observed, each under one time per hour. Figure 1 below shows these frequencies.

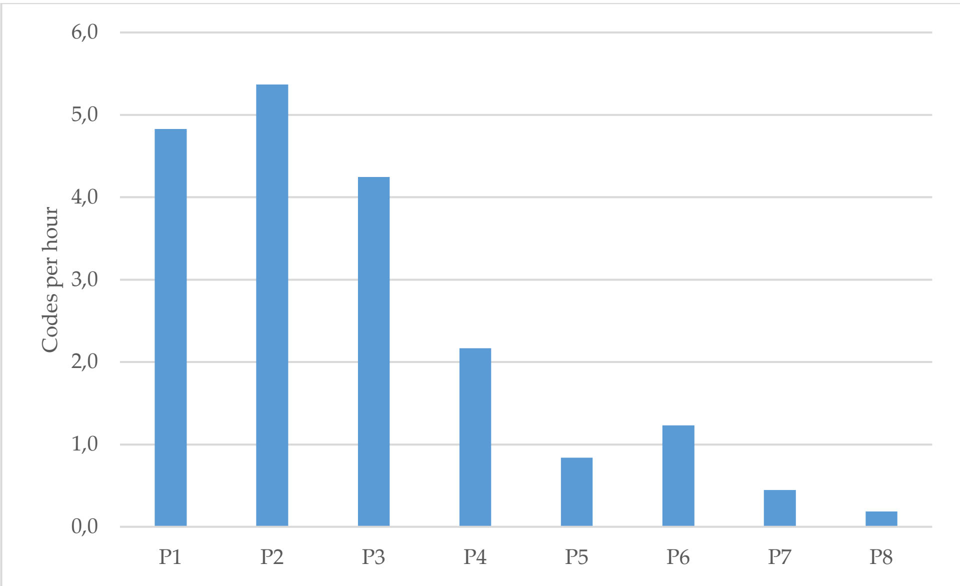

Figure 1. Practice frequencies (all sites)

It is clear that preschool-age children are frequently engaging in science and engineering practices while at play. They engage most frequently in asking questions (P1), developing and using models (P2), and planning and carrying out investigations. This is true across all four sites in our study, despite the significant environmental, pedagogical, and demographic differences among these sites. These frequencies are not particularly surprising to anyone who has worked with or raised children, since much of play involves investigating one's surroundings, asking questions that arise in those investigations, and because pretend play requires the ability to transform objects and actions, assigning them with symbolic meaning (Bergen, 2002), a skill directly related to modeling practice. For instance, we observed numerous examples of children playing with toy cars or trucks and speaking about them as “toys”. These instances were coded as P2c because children demonstrated that they could “distinguish between a model and the actual object, process, and/or events model represents” (Table 1). However, in some instances children transform those toy replicas through pretend play as when one child lifted a toy truck off of the ground and began “flying it” through the air while making noises associated with a rocket or an airplane. This instance was coded as P2b because the child was using the object at hand (a toy truck) to represent something else (an airplane).

When we examine the distribution of SEPs by site (Figure 2), we find that overall, the total number of practices observed at each site does not vary significantly; sites range from 20.1 practices (Site B) to 26 practices (Site D) per hour.

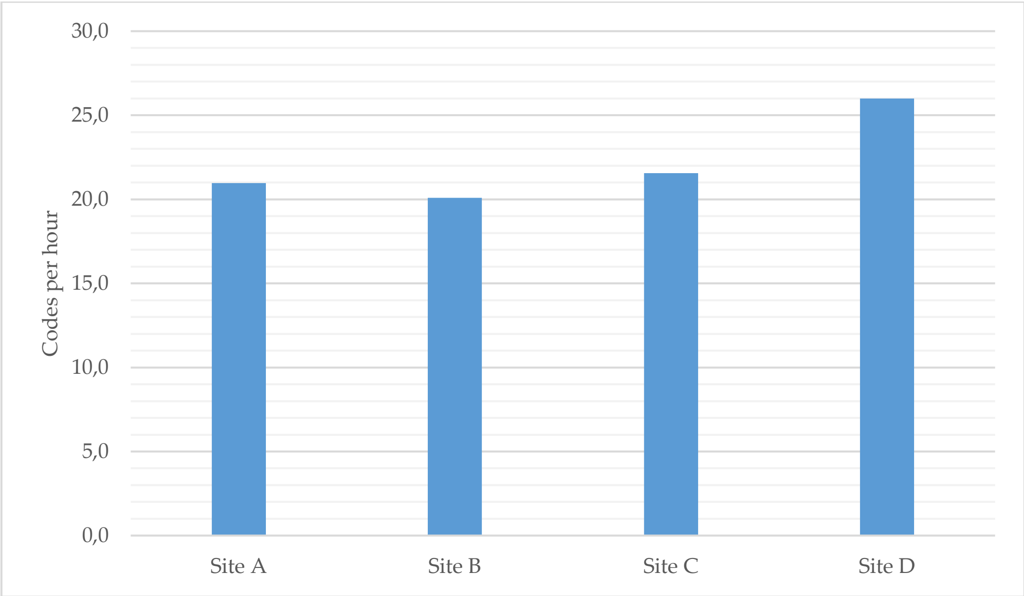

Figure 2. Total number of practices by site

Similarly, we captured SEPs at all proficiency levels – Emergent (C), Proficient (B), and Exemplary (A) in our observations. As seen in Figure 3 below, the differences across levels are large; frequency of practices is lowest at level A (0.74 codes per hour) and highest at level C (17.68 codes per hour). This is expected, as the practices and our corresponding levels are benchmarked to the K-2 NGSS standards, and our sample is younger and more likely to be at the earliest stages of these emerging practices.

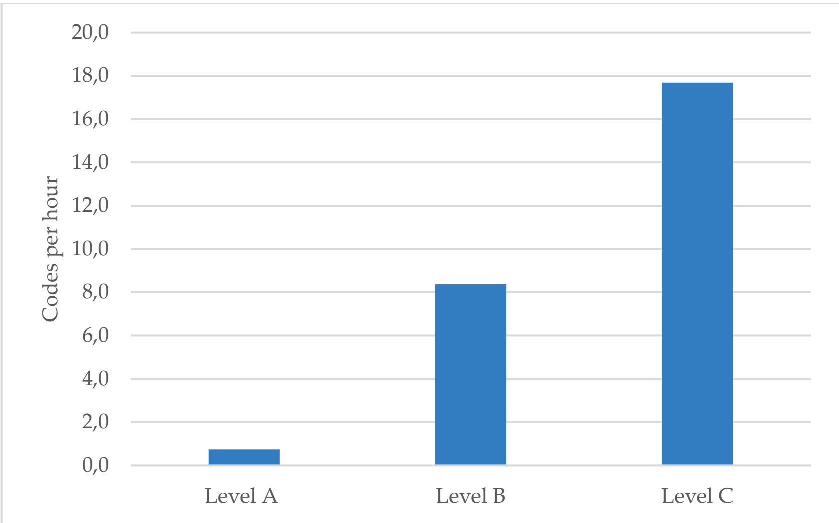

Figure 3. Level frequencies all sites

If we break these patterns down further, we see some site-based patterns emerge (Figure 4). Level A practices are observed much more often at Site A (1.85 codes per hour), fewer than half as much at Site B (0.69 codes per hour), and almost never at Site C or D. Conversely, Level C practices are observed most frequently at Site C (18.39 codes per hour) and Site D (19.67 codes per hour). Our transcripts also reveal that engagements in practice at level C are often fleeting, in situations where children begin to explore or engage in a particular way but then get distracted or disrupted and move to something else. These vignettes tend to be shorter than instances where children are more deeply engaged in play-based exploration or problem-solving and so it stands to reason that observers would see higher frequency counts of these more nascent practices (which are often incomplete engagements).

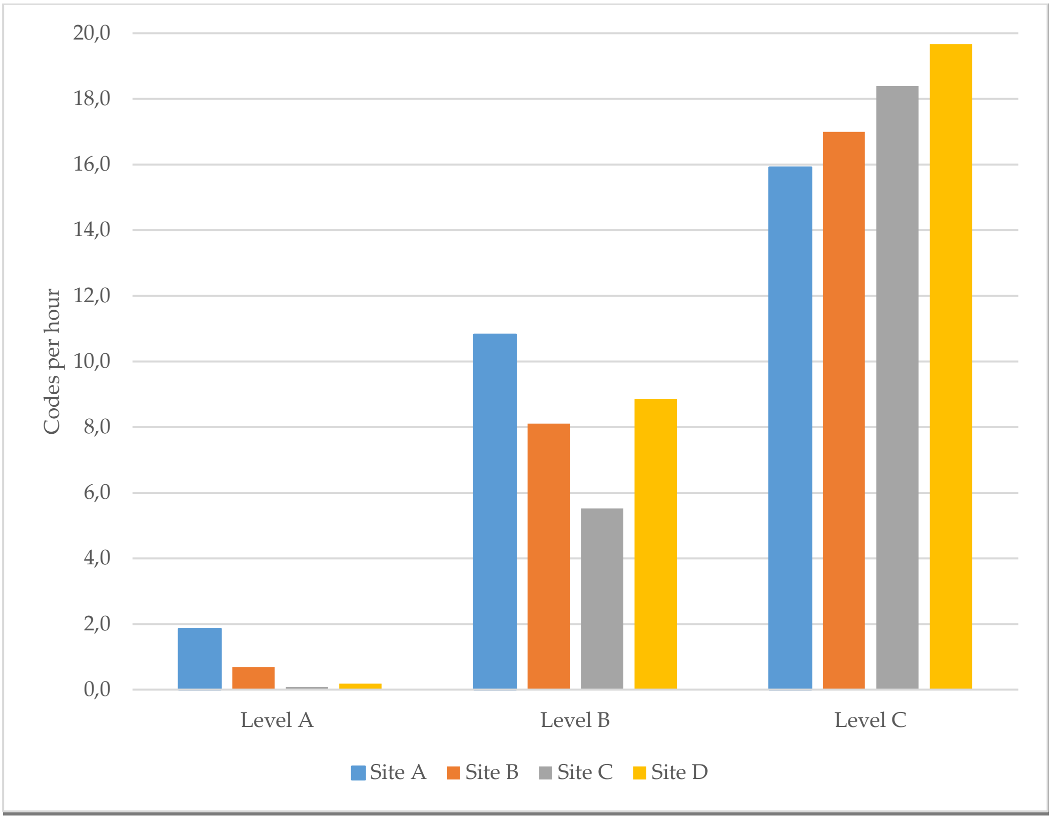

Figure 4. Level frequencies by site

For example, we documented more than 340 instances of P4c; this emergent level of analyzing and interpreting data includes instances where children collect and/or record data (including observations or measurements), recall previously collected data, or recognize patterns in the world. Frequently, P4c codes were used to capture children making single observations; these ranged from noticing changes in weather (e.g., "It's raining"; "This sand is all wet") to observing what happened when a teacher tipped a jar of applesauce upside down and began tapping it to refill a bowl (i.e., "Some applesauce just came out!"). These engagements were often fleeting. For an instance to be coded at P4b children must "create or describe patterns or relationships in the natural or designed world" (Appendix F) (NGSS Lead States, 2013). In other words, children must use multiple data points in order to interpret something they measure or observe. The conversation that follows was recorded at Site D during snack time:

[children sitting around a table having snacks]
Student 1: [looking towards a window] Why is the world...why is the world.... Why is the world going up?
Teacher: Why is what going up? [child points toward the window, T turns around and looks] Why is the world going up? Do you mean the Sun?
Student 1: [nods, mutters inaudibly]
Teacher: The Sun goes up. That's what it does. It rises... in the morning.
Student 2: The Sun goes up...
Student 3: And when does the Moon go up?
Teacher: When does the Moon go up?

[multiple students talk at same time]
Student 3: It goes up at night time!
Student 4: And then the Moon goes up, and then it's bedtime! And then we go to bed and go to sleep.
Student 1: The Sun goes down and the Moon comes up and then it's time for bedtime.
Student 2: Yeah. When the Sun comes up, it's not bedtime.

In this instance, Student 1 looks through the classroom window and makes an observation about the sun rising. This is followed by children making sense of what they know about Sunrise and Moonrise: that one is associated with morning, and one is associated with night or "bedtime". These observations are pulled from both the present (Student 1 observing the Sun outside) and from recalled observational data (children indicate familiarity with day and night cycles).

Our final illustrative example is of P4a; Benchmarks for P4a on the SciEPOP include "Analyze data to determine if a tool, object, or process 'works'" and "Analyze data to answer scientific questions and solve problems". In the example that follows (Figure 5), students make observations about a pretend birthday cake (P2b) and figure out how many (stick) candles they need before critiquing and revising their model (P2a) to account for their interpretation of the observational data (about the weight of mud versus dirt on top of the 'cake'):

Student 2: Can I have another candle? Because someone is going to be ten.
Student 3: I need ten candles. So I need six more, I think.
Student 4: So you have, [pointing as she counts] 1, 2, 3, 4, 5...
Student 3: I have seven.
Student 4: So you need three more.
Student 3: Here are your three more so you have ten!
Student 5: We have ten candles in ours!
Student 2: I'm going to light mine
Student 1: Do you want to do mud on top of them? [drizzles mud on top of one stick] Oh no!
Student 2: What!?
Student 1: It's falling over! I have some more mud...
Student 4: The MUD makes it heavier, so it tipped over.
Student 3: Yeah. We don't have mud, so it stays.
Student 1: [to Student 2] Do you want to do dirt like them?
Student 2: Yeah. Yes.
Student 1: Let's do dirt like them. [Student 2 begins to sprinkle dirt on top]
Student 4: We're not putting dirt on top of them [sticks/candles]
Student 2: On top of the cake! [continues to sprinkle dirt]

Figure 5. Children use mathematics and make observations about the "candles" in their "cakes"

Engagement with Practice 4 may happen in a matter of seconds, as with a single observation about the weather or may be sustained over several minutes or longer as children engaged deeply in observation, analysis, and interpretation of the data at hand.

Teacher Pedagogy in Play

When teachers engage with children at play, they are necessarily influencing children's behavior and thinking, even when that influence is not apparent. Some types of pedagogical practices are more influential than others; for example, a teacher who notices a child experimenting with using a stick as a lever might say, “Be careful!” This interjection might result in the child pausing, or reconsidering their actions, but is unlikely to push the child into further investigation. However, a teacher that intervenes to say, “What do you notice when you use that stick to lift heavy rocks?” is likely prompting children to explore the science and engineering elements of their play.

Teacher behavior, like student learning, is multifaceted and difficult to predict. Some behavior, however, is shaped by the site itself; preschools develop and train their employees to enact a particular set of norms and values in their work. When these sites differ in the ways they prepare teachers, we expect to see differences in the types and frequencies of teachers’ engagement with students at play. Our analysis bears this out. Figure 6 below shows the distribution of total pedagogy codes by site.

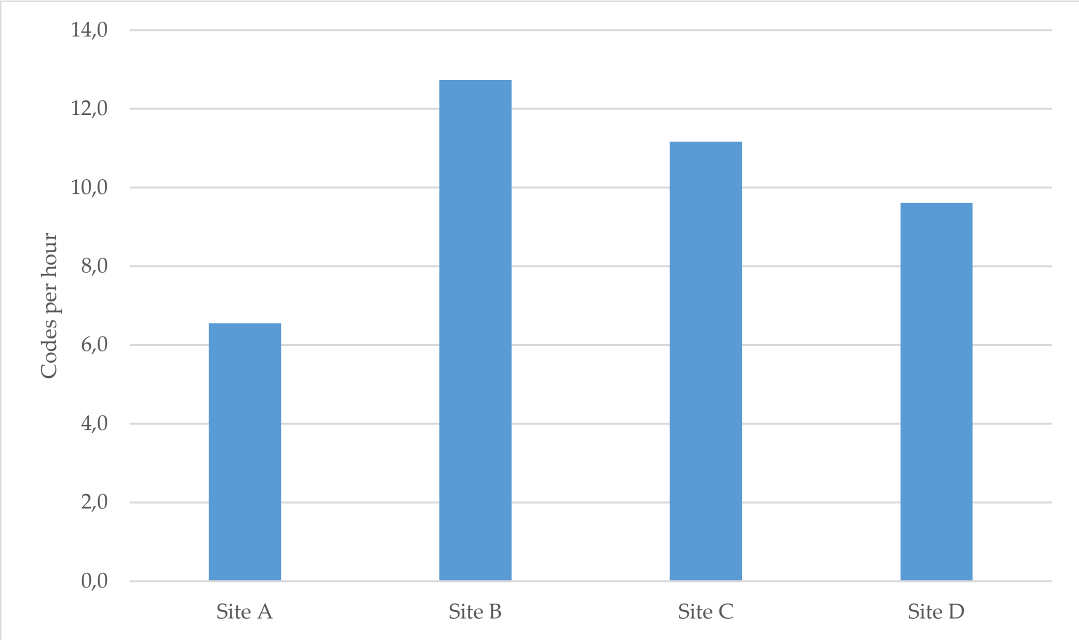

Figure 6. Total pedagogy codes by site

As seen clearly in Figure 6, teacher intervention during children’s play happens least frequently at Site A (6.56 codes per hour), and most frequently at Site B (12.73 codes per hour). This difference between Site A and B is important, because both sites purport to have similar approaches to space and play.

When we look at the breakdown of individual pedagogy codes in Figure 7, another clear pattern that emerges is the relative low frequency across all teacher pedagogy codes at Site A compared to other sites.

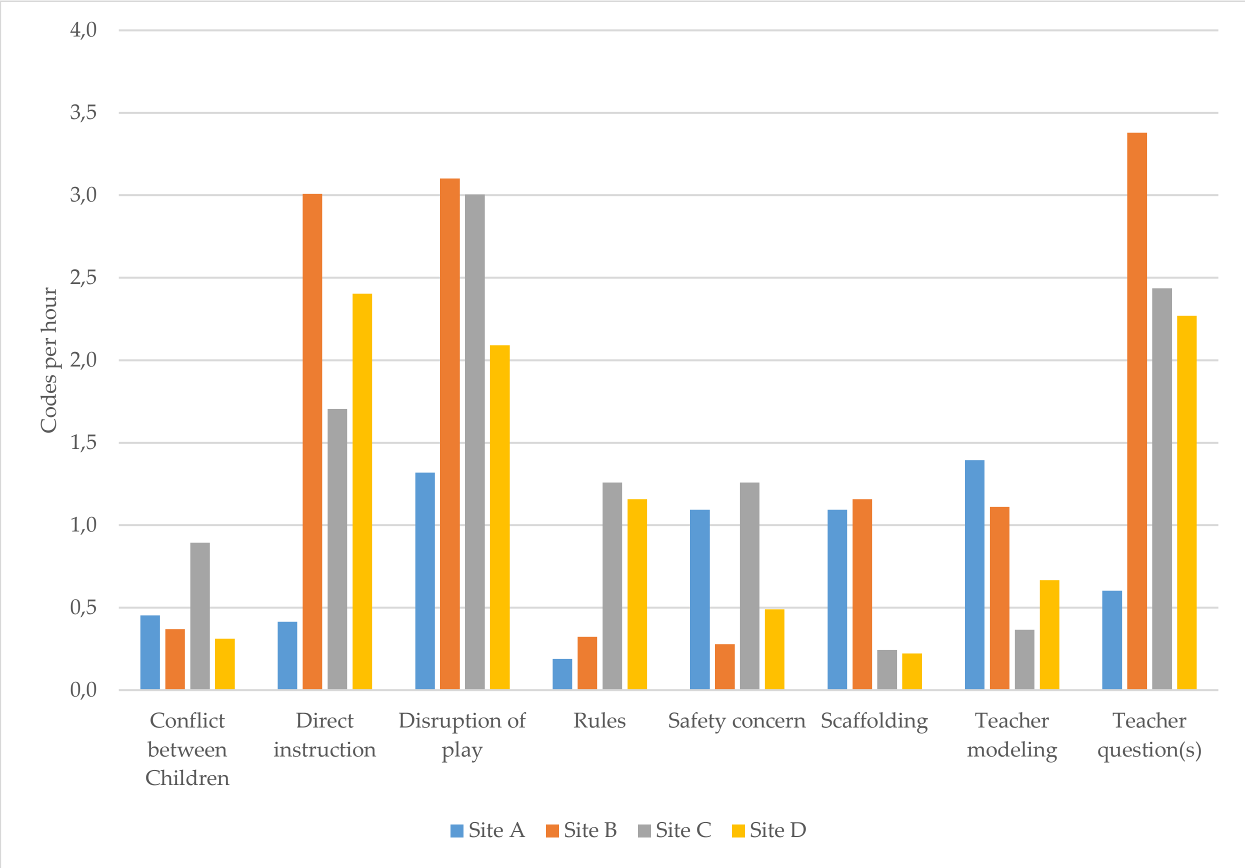

Figure 7. Individual pedagogy codes by site

This is especially true among the codes for direct instruction, disruption of play, rules, and teacher questions. Site B, on the other hand, exhibited the highest frequency of interactions for direct instruction, disruption of play, and teacher questions. The stark differences in teacher pedagogy between Sites A and B is revealing, as while both sites describe their approach as "play-based," Site A is centered around close teacher-student relationships and "uninterrupted play". At Site A instances of direct instruction were infrequent, with teachers more often modeling particular behaviors (e.g., digging or stacking loose parts) or quietly scaffolding children's play (e.g., placing additional tools or materials near a group of children engaged in exploratory play). By contrast, Site B emphasizes academic and social school readiness and touts "data utilization" as a "core feature" of their model. It is not surprising then that we saw the highest frequencies of direct instruction and teacher questions codes at Site B. The significantly higher rates of "rules" interventions by teachers at Sites C and D is reflective of their emphasis on childcare and behavior management.

To get a better understanding of how teachers' patterns of interaction varied by site, we grouped pedagogy codes into two categories: management codes and play facilitation codes. These categories reflect an important conceptual difference in our analysis between actions that *support* science-engaged play and actions that *hinder* science-engaged play. Management codes include: safety concern, disruption of play, rules, and conflict among children. Play facilitation codes include: direct instruction, scaffolding, and teacher modeling. Teacher questions were analyzed as a separate category, as we expect in future analyses to find that these questions differ by type. Figure 8 shows the patterns of these categories across sites.

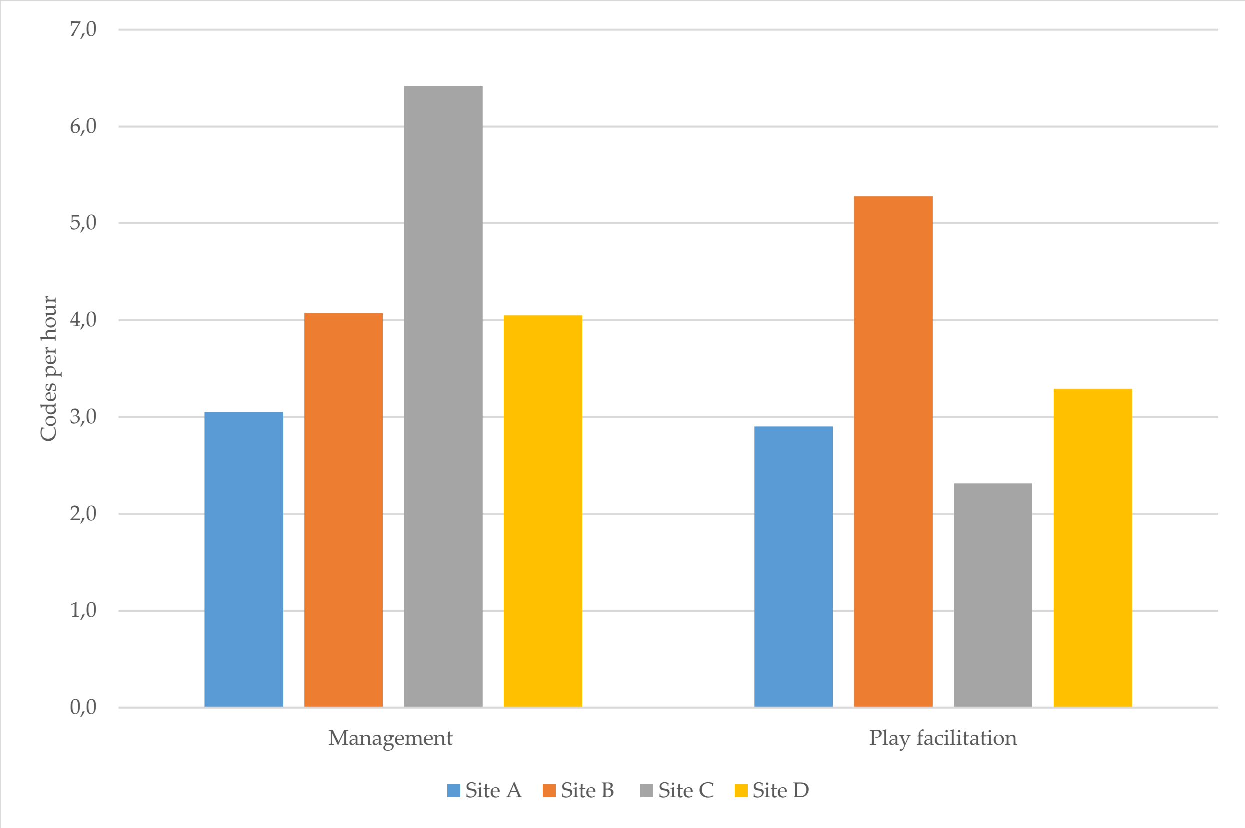

Figure 8. Pedagogy categories by site

When teacher interventions are grouped into "management" and "learning support, clear differences emerge across the four sites. Teachers at Site C engaged in management pedagogies more frequently than other sites, and engaged in play facilitation pedagogies least often. At Site B, teachers engaged in play facilitation pedagogies most often. Overall, teachers at Site A engaged in management and play facilitation at similar frequencies.

Relationship between Pedagogy and SEPs

Our analysis in this section focuses on the relationship between pedagogy and SEPs. Figure 7 shows the distributions of intersecting pedagogy codes at each practice level. The patterns of intersection are similar across all three practice levels; "disruption of play" and "direct instruction" are the two most commonly occurring and overlapping codes at each level. For example, at Level A, the most frequent intersections are with "disruption of play" (4.65 intersections per hour) and "direct instruction" (3.4 intersections per hour).

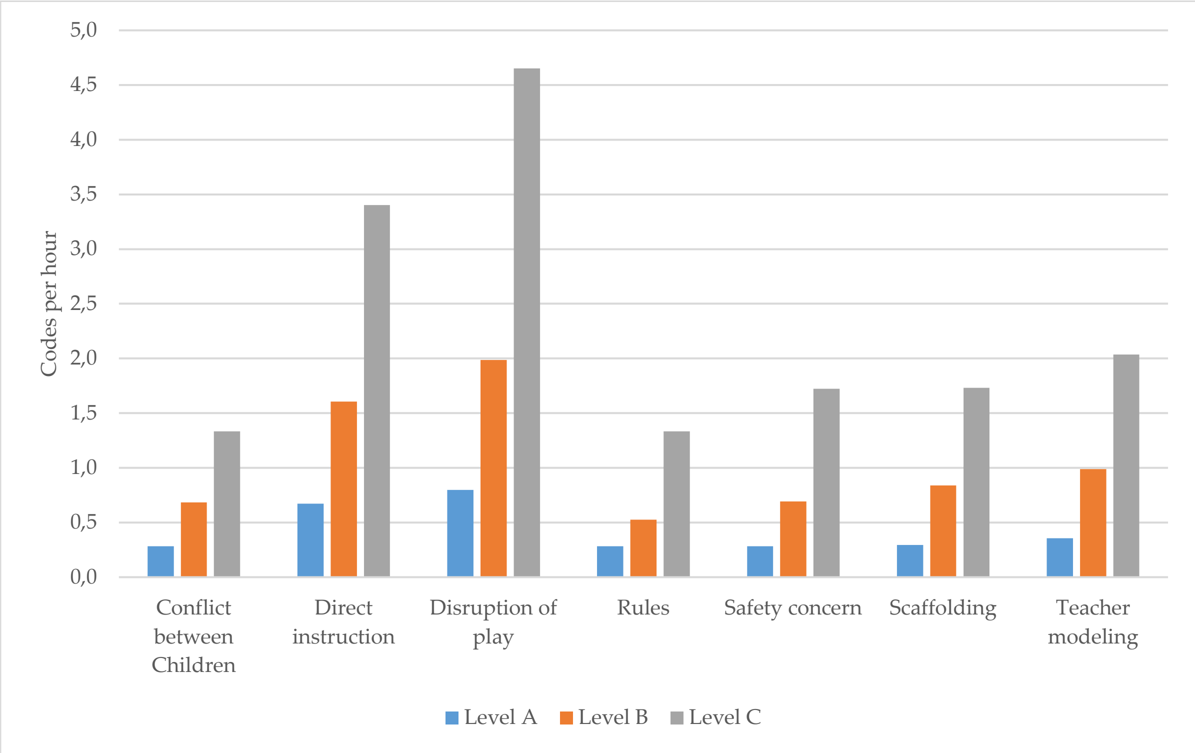

Figure 9. All pedagogy codes by practice level

These pedagogical practices share an important feature – a teacher interrupting to place themselves at the center of children's play. Though direct instruction may offer a chance for children to receive relevant, science-specific information, it also risks interrupting the play that allows for creative self-guided exploration of science and engineering. This approach is in specific contrast with Site A, which promotes "uninterrupted play" as key to children's learning, and where we observed the lowest rates of disruption *and* the highest rates of Level A practices.

Contextualizing the Relationship between Teacher Pedagogy and Students' Science Practices

In the section that follows, we will provide greater context for the relationships we see in the data between teacher's pedagogy and children's engagement with play-based SEPs. We will present excerpts from video transcripts, noting where children are engaging with nascent SEPs. Further, we will present analysis of teacher pedagogy related to these instances.

Nature-Based Water Play with Teacher Scaffolding

In the transcript excerpts that follow, children are playing in water flowing from a hose down an embankment and into the gully that runs under a footbridge on the play yard. Two children begin this investigation around flowing water as a teacher observes from the footbridge above. They are quickly joined by other curious preschoolers and the purpose of their play shifts from investigation of water flow (science) in Figure 11 to problem solving with the children removing obstacles to make the water flow under the bridge(engineering) in Figure 12 (Cunningham, 2017; Cunningham & Carlsen, 2014).

Figure 10. Children observe flowing water from a hose

1 Student 1: Give me more dirt
2 Student 2: Why?
3 Teacher: [explains to another child] He's asking [child name] for more dirt so he can block the hole.
4 You could ask him, "why do you want to block the hole"?
5 Student 3: [repeating] Why do you want to block the hole?
6 Student 1: So it [water] doesn't go that way.
7 Student 2: And I'm still working on that rock [inaudible]...
8 Teacher: You're still working on how to get that rock out of the ground.
9 Student 2: Oh look! It's drying all up!
10 Teacher: Well, why do you think it's drying all up?
11 Student 2: Oh, wait! The dirt is pushing it now. If the dirt pushes it, it will go more backwards.
12 Student 1: Wait. Here it comes faster 'cause I took some dirt out of the way.
13 Student 2: Yes. Now let's try and move this rock. We need more muscles.
14 Student 1: That means [child name] has to help again.
15 Student 4: I can help...[inaudible]

In the beginning of this excerpt, the children are negotiating their purpose (P3: Planning and Carrying Out an Investigation). One child is already manipulating the flow of water down the embankment by moving and shaping the dirt in its path. After asking a questions (lines 2 and 5) to clarify what Student 1 is doing, Students 2 and 3 join him in an attempt to clear weeds and rocks from the water's path. Both Students 1 and 2 make observations about the flow of water (lines 9, 11, and 12), and the teacher observes from above, modeling questions for the children like, "You could ask him, 'why do you want to block the hole?'". The children use observational data to inform what they do next as their teacher models the types of questions they might ask (lines 3-4) and scaffolds their investigation with well-placed questions (e.g., "Well, why do you think it's drying all up?").

Figure 11. Children alter the flow of the water by removing obstacles

16 Teacher: Another set of hands is coming. He's trying to pull that weed. Can you help him pull that weed? 17 How did it get there?
18 [Student 4 and Student 2 both pull at the weed, S4 rips a large part of the week up]
19 Student 2: Super strong muscles!
20 Teacher: There! You got part of it. You DO have muscles. Right at the root; you got it!
21 Student 4: Why is it so...[inaudible]?
22 Teacher: Uh oh, I think they need more help. They need two more hands. Who's hands can help them pull 23 that? Do you have two more strong hands?
24 S: Maybe we need SEVEN hands
25 [Three children now working on pulling the weed by the rock they were trying to move]
26 Teacher: Pull [child name] pull! Do you hear it cracking? Listen when you do it.
27 Student 1: Now we need EIGHT HANDS!
28 Student: I heard it!
29 Teacher: Oh! Are you going to help? Perfect! I'll bet you [child name] can help.
30 Student 2: Eight hands! Eight hands! [three children are pulling at this point]
31 Student 1: Put two more hands on and we'll have eight hands!
32 [four children are pulling - one child appears to be pulling in the opposite direction]
33 Student 1: No! Not that way. This way!
34 Student 5: It's not coming! [All children take turns tugging] It's stuck
35 Student 3: Here comes more water because I'm digging it! [scooping water and dirt along the path of the 36 water] I'm getting more dirt out.
37 Teacher: You know what, [child name]? It looks like you are really determined to get that. Uh! Part of it.
38 You gotta go right to the root. You remember where the roots are? Right at the very bottom?
39 Student 5: It's stuck! Its stuck!
40 Student 1: Woah! Here it [water] comes faster! It's coming faster, guys!
41 [Student 3 tugs and stumbles backward as he pulls the weed from the ground]
42 Teacher: Woah! He did it! Nice job, [child name]!
43 Student 4: How did he do that?
44 Teacher: Well I think you guys loosened it and he came right in and pulled it out.
45 Student 3: I'm strong.
46 Student 2: What!? You're strong [child name].
47 Student 1: Well, he's not very stronger than us. You're not stronger than us, [child name].

In the second part of this vignette the teacher continues to ask probing questions (e.g., "How did it get there?"; "You remember where the roots are?") and to scaffold their investigation and problem solving (e.g., "They need two more hands. Who's hands can help them pull that?"). Meanwhile, the children continue their efforts to remove weeds and rocks such that they can direct the path of the water until it flows under the bridge. In this effort they determine they need ever more strength to pull stubborn weeds and heavy rocks. They use math (P5) as they articulate "how many hands" it will take to pull out a particularly stubborn weed (lines 24, 27, 30-31). "Eight hands! Eight hands!, one student exclaims. A second student notes that at that time there are three children are pulling (3 x 2 = 6) and says, "Put two more hands on and we'll have eight hands!". During this time, the teacher continues to narrate what is happening (e.g., "Another set of hands is coming. He's trying to pull that weed".) and asking questions like, "Can you help him pull that weed?". The teacher alternates between observing and asking questions to scaffold the children's investigation. She also encourages the children saying things like, "It looks like you are really determined to get that". Finally, in Figure 12, the children notice that their efforts succeed as the water begins to flow faster (lines 33-36; 41).

Figure 12. Children investigating under a bridge

48 [Children pull another weed and then are able to roll the rock away]
49 Student 2: We really did need to move that weed.
50 Student 1: Who can help me move the dirt? Who can help me move the dirt?
51 Student 2: Thanks for team-working! You really do have strong muscles, [child name]
52 Teacher: Didn't we say something about teamwork works amazing? That was proof of that, wasn't it?
53 Student 2: Yeah. And me and [child name] and [child name] all helped, and we loosened it for [child 54 name]. We loosened it.
55 Teacher: What did you get the spoon for, [child name]? What are you going to do with it?
56 Student 1: To dig the roots! [Teacher name], I'm going to see if the water is coming under the bridge!
57 Teacher: Is it coming under yet?
58 Student 1: Oh! It's coming under guys!
59 Student 2: It is! [Runs up and over to other side of the bridge]
60 Student 3: It's coming under the bridge!
61 Student 1: It's coming under the bridge, guys!
62 Student 2: Oh, yes it is! [child name], look under the bridge. That's cool! We really did do it!

After making additional (P4) observations (e.g., "we really did need to move that weed") the children finally achieve their goal, as multiple children notice that "It's [water] coming under the bridge"! Over this extended play–based engagement, the group of children engaged with five SEPs, persisting until they achieved their goal, to engineer the embankment such that they could control the flow of water from the hose to run under the footbridge. In all of this, the teacher stood as a careful observer, narrating the scene, asking questions, and encouraging children without ever involving herself directly in their play or disrupting their play.

Discussion & Implications

Our findings reveal that preschool-aged children are engaging in SEPs at play frequently and at emerging, proficient, and exemplary levels. We have captured the breadth (practices) and depth (levels) of children's engagement with SEPs, as well as the pedagogical moves that teachers make when children are playing. We see notable differences in these areas across our four sites, which we argue can, in part, be explained by their specific approaches to play and learning. Site A, which emphasizes secure, attached relationships, and specifically *uninterrupted* nature-based play, is the site where we see both the lowest frequency of teacher interventions during children's engagement with SEPs, and the greatest frequency of

Level A practices. This juxtaposition of fewer teacher interactions with more sophisticated (Level A) enactments of SEPs may initially seem counterintuitive, but considering that deeper engagement with play requires longer periods of undisrupted time, these patterns make sense. Conversely, when we look at Site C, there are a significant number of Level C (Emergent) practice codes, but Site C has the fewest number of Level B practices and virtually no Level A practices. However, when we aggregated teacher pedagogy codes into groups related to "Facilitation of play" and "Management", Site C had the greatest number of "Management" codes across all four sites. This may indicate that children are engaging with SEPs at a superficial level but that they face frequent disruptions to their play and are, therefore, less likely to move into the more deeply engaged play that appears to foster higher-level engagement with SEPs.

While there is ample research to suggest that play should be central to early childhood science learning (Akman & Özgül, 2015; Bergen, 2009; Bulunuz, 2013; Cook et al., 2011; Larimore, 2020), there is wide variation in how play is defined, managed, and supported across EC programs. All four preschools in this study described their programs as "play-based" yet we have identified notable differences in the spaces, materials, and pedagogies children encounter across those four participating preschools. These differences suggest significant gaps in children's opportunities to engage in and deepen their enactment of SEPs while exploring the world around them, and raise questions about equity in early science learning environments that have implications both nationally and internationally for science education practice, research, and policy.

Conclusion

Play is an essential component of children's early learning; however, in order for children to learn and develop through play, they must have access to the time, space, materials, and pedagogy that support it. Preschool settings offer these possibilities, though not all settings emphasize play equally – a fact we observed in our research sites. Scholars have echoed the call from the United Nations (1989) to frame play as a right and not a privilege (Ladson-Billings 2006, 2011; Souto-Manning, 2017). Souto-Manning (2017) posits that in low-income preschools there is a heavy focus on behavioral management and standardization whereas in more affluent preschools, there is much more unfettered, self-directed, "free-play". She links free play to children's agency, arguing that, "In play, children are agents. They are doers... If we are to unleash children's infinite potential, not only do we have a responsibility to position play as a right, we must also understand the agency children need to have during play" (p.786).

Further research is needed to determine how and to what extent the complex interactions among access to play, space and materials, and pedagogical strategies shape children's engagement with SEPs. The patterns we have identified in this paper suggest that each plays an important role; teasing out these roles will provide valuable insight into how ECE programs and teachers can support deep, meaningful science learning without sacrificing play. Time may also play an important role in supporting more sophisticated engagement with SEPs in play; we have noted, anecdotally, instances in which extended play-based scenarios offer greater opportunities for progression along practice levels. Future research may explore this relationship in more detail. Finally, we see great opportunity for early childhood teachers and administrators to use the SciEPOP as both a training and instructional tool. We believe that teachers and school staff can be trained to use the SciEPOP to learn how to identify and support children's emerging engagements with science and engineering practices, specifically at play.

We assert that by increasing and supporting opportunities for deep, engaged play, teachers are necessarily creating opportunities for children to engage in SEPs. This means, quite often, that the best way for teachers to support science learning among preschool children is to stand back – or, at most, to intervene only in ways that facilitate play. These types of pedagogical skills take practice to hone, but they can be supported by both institutional guidelines and professional development. The evidence offered in this paper suggests that teacher professional development is a powerful tool to help mitigate notoriously low science self-efficacy among early childhood educators (Barenthien et al., 2018; Gerde et al., 2018; Greenfield et al., 2009; Saçkes, 2014) and increase children's opportunities to learn science through play.

Declarations

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Appendix A: Presep Instrument: Observing Preschool Science & Engineering Practices in Play

<table>
<tr><th>Practice Code</th><th>Time</th><th>Level
A ǀ B ǀ C</th><th>Pedagogy Codes
DP ǀ DI ǀ C ǀ SC ǀ S ǀ TM ǀ TQ</th><th>P1: Questions
IS ǀ B</th><th>P8: Information
V ǀ W ǀ O</th><th>Physical Space</th><th>Incident Notes</th></tr>
<tr><td rowspan="3">P2: Developing & Using Models</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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<tr><td rowspan="3">P3: Planning & Carrying Out Investigations</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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<tr><td rowspan="3">P4: Analyzing & Interpreting Data</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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<tr><td rowspan="3">P5: Using Mathematics & Computational Thinking</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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<tr><td rowspan="3">P6: Constructing Explanations & Designing Solutions</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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<tr><td rowspan="3">P7: Engaging in Argument from Evidence</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="8">Incidental Questions (running tally)</td></tr>
<tr><td colspan="8">Observer Notes</td></tr>
</table>

Time

Mark the beginning and ending time of each incident.

Practice Levels

A	Exemplary
B	Proficient
C	Emergent

Pedagogy Codes

DP	Disruption of play
DI	Direct instruction
C	Conflict between children
SC	Safety concerns
S	Scaffolding
TM	Teacher modeling
TQ	Teacher questions

P1 and P8: Questions and Information

For P1, code the types of questions asked during incidents. For P8, code the specific ways students share or receive scientific information.

P1: Questions		**P8: Information**	
IS	Information seeking	**V**	Visual
B	Building	**W**	Written
		O	Oral

Physical Space

Describe key characteristics of the physical environment in which the incident takes place; note the physical space (i.e. outdoor playspace; classroom playspace) as well as key materials present (i.e. shovels & buckets; play structure)

Incident Notes

Note key details about the incident not captured otherwise by the instrument (i.e. topic of investigation, number of children present).

Incidental Questions

Mark a running tally of observed questions that are not captured in a coded incident.

Observer Notes

Note key details about the observation not otherwise captured by the instrument (i.e. total time of observation, time of day/season/weather, other adults present, important contextual factors).