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Data collection and analysis for preschoolers: An engaging context for integrating mathematics and computational thinking with digital tools

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ABSTRACT

Collecting and organizing data to understand and answer real-world questions is an increasingly important skill in our current world. Fostering data collection and analysis (DCA) skills in young children leverages key mathematics skills as well as the data representation, visualization, and interpretation skills of computational thinking (CT), culminating in a problem-solving approach with data. As such, the intervention, comprising investigations and a digital app, supported preschool teachers and children to answer data-focused questions by engaging in each step of the DCA process in order to foster CT and math skills. Teachers appreciated that the app offers a new way for children to visualize data and noted that the app provided learning opportunities for children that would not otherwise be possible or easy to implement. Results also suggest that the app provides a systematic process for data collection, entry, and interpretation. Children in classrooms that completed the intervention had significantly higher scores at post-intervention compared to children in classrooms that did not complete the intervention, controlling for pre-intervention scores, B(SE) = 0.13(0.05), t (6) = 2.48, p = .048.

The goal of the Preschool Data Collection and Analysis (DCA) intervention is to use curricular investigations with data to foster mathematics and early problem-solving skills in preschool children. By engaging in investigations that involve collection, analysis, and discussion of data, preschool children and teachers collaborate to build mathematics skills related to counting, sorting, classifying, comparing, and ordering, as well as problem-solving skills such as creating and comparing representations to effectively communicate quantitative information and answer research questions. A key component of the intervention is the *Preschool Data Toolbox*, a tablet-based, teacher-facing digital app to support the collaboration of preschool teachers and children in collecting data, creating simple graphs, and using the graphs to answer real-world questions.

DCA is a critical and new area of focus, especially in preschool. However, it is an area of great importance in our data-driven world and is an area in which preschool children naturally gravitate and excel. For example, curious preschoolers ask questions about the weather and what they should wear to be comfortable or what kinds of activities they can do on a day with that weather; about patterns they notice in nature or their indoor environments; about their schedules and routines, such as how they get to school or what is for lunch or snack; about the sizes and ages and other attributes of friends and animals; and so on. As they ask these questions, they must consider what information is needed to answer their questions, where they might find that information, how they might collect it, how they might organize it to examine it, and what that information can tell them that is useful and relevant to their questions. All of these skills are the ones we highlight in our DCA intervention.

Furthermore, our intervention was designed to support teachers and students in learning and applying DCA skills *and* to integrate these into their own pedagogical toolkit as they learn about other curricular areas throughout the school year. The intervention begins with six researcher-developed investigations, then provides scaffolding for teachers to create two of their own investigations, and finally scaffolds teachers and students in selecting multiple research questions around a central theme to design their own data story. This final data story not only consolidates many of the skills learned along the way, but also provides a meaningful context for seeing the value of data in increasing our understanding of the world around us and in telling stories from our collective observations. Together, these intentional principles of design allow DCA to live on beyond the scope of our study and to be infused across topic areas.

This article presents findings from a second design-based research study using a mixed-methods approach. It focused on the intervention's developmental appropriateness and feasibility and identified necessary changes to the investigations, app, and professional development to allow teachers to implement DCA activities effectively and children to learn the target skills. This study follows a previous pilot study in which

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the intervention, digital tools, and professional development were revised in response to findings (Blinded for peer review). The resulting improvements were tested with a new and larger set of preschool teachers and children. We collected data related to children's learning, teachers' implementation, and beneficial supports to identify new and remaining challenges requiring revision to the final intervention activities and teacher professional supports.

1. Problem-solving with data: computational thinking in early childhood

To foster preschoolers' problem-solving skills in mathematics, we applied a *computational thinking (CT)* lens and extended the CT standards of "data and analysis" (K–12 Computer Skills Framework CSF, 2016) into preK. While definitions of CT vary, one perspective considers CT to be a practice or thought process that applies foundational computer science concepts to solving problems and clarifies that CT is a set of *thinking skills* that apply in everyday settings (Wing, 2006, 2008) where CT is thinking like a computer scientist, not like a computer (Wing, 2006). Another perspective defines CT within mathematics and science education, such as *A Framework for K-12 Science Education* which defines CT as utilizing computational tools (e.g., programming simulations and models) grounded in mathematics to collect, generate, and analyze large data sets, identify patterns and relationships, and model complex phenomena in ways that were previously impossible (National Research Council, 2012). Acevedo-Borrega, Valverde-Berrocoso and Garrido-Arroyo (2022) describe CT literature in terms of concepts, practices, and perspectives, noting that the most developed CT concepts related to "data, algorithms, and sequences," while the most developed practices relate to "testing, data analysis, and debugging (p.5)." While young children would not be expected to analyze large data sets, and tools for creating models may not be developmentally appropriate, exposing young children to the ways that computers or tablets can assist in the problem-solving process is also important to computational thinking (National Research Council, 2010) and provides students with a "tool to think with" (Papert, 1980).

While discussions of the meaning of CT continue, there has been limited consensus on how it should be operationalized in education (Barr & Stephenson, 2011; Wang, Shen & Chao, 2022) and crossing disciplines increases the range of definitions. For our purpose of supporting problem-solving in preschool mathematics, we followed a science and mathematics-centered approach which connects CT and mathematics by supporting DCA, testing hypotheses productively and efficiently, and views CT as an overarching sense-making process (Shin et al., 2022; Weintrop et al., 2016). Specifically, our approach aligns with the International Society for Technology in Education (ISTE) and Computer Science Teachers Association (CSTA) 2011 definition, who defined CT in K–12 education as a problem-solving process that includes formulating problems in such a way that enables the use of technology to help solve them, collecting, organizing, and analyzing data logically, representing data through models and simulations, achieving efficient and effective solutions, and generalizing and transferring to other problems.

Although research is limited around the integration of CT into mathematics education (Wang et al., 2022) and into early childhood classrooms (McCormick & Hall, 2021), current CT frameworks focus on a series of core concepts that can be applied to young children (blinded for peer review). Research suggests that CT skills are associated with academic and analytic skills for adults (Van Dyne & Braun, 2014) and academic achievement for elementary school students (Oliveira, Nicoletti & Cura, 2014). Furthermore, just as young children can engage effectively with coding and computational problem-solving (Bers, 2019; Bers & Resnick, 2015; Elkin, Sullivan & Bers, 2016; McLennan, 2017; Papadakis, Kalogiannakis & Zaranis, 2016), they can also engage effectively with CT through apps (Papadakis, 2022) and working with robots (Bakala, Gerosa, Hourcade & Tejera, 2021; Gerosa, Koleszar, Gomez-Sena, Tejera & Carboni, 2019). Given the relationship between CT and academic achievement as well as young children's capacity to learn CT, there is a trend toward integrating CT skills with other content for preschool-aged children (Grover et al., 2019; Blinded for peer review).

From a disciplinary perspective, CT in mathematics can be considered a problem-solving process with core components that overlap with the content strand of DCA, including asking questions and then collecting, organizing, representing, and analyzing data with the goal of efficiently addressing real-world problems (Barr & Stephenson, 2011; ISTE & CSTA, 2011; Weintrop et al., 2016). *In this way, CT is the problem-solving/sense-making process children use, and DCA and computers/tablets are the tools children employ to answer real-world questions by figuring out which data are relevant, organizing it in ways that illustrate meaning and utility, and interpreting that data to solve real-world problems.*

2. Data collection and analysis: a tool for sense-making

In early childhood, we argue that data collection and analysis is a critical tool for sense-making and problem-solving. Young children are constantly collecting, sorting, and organizing data and using it to make sense of the world around them and to predict future actions or outcomes (Platas, 2017). While this may come naturally to children, they need teachers to make this invisible process visible. Specifically, we contend that one approach to supporting the development of problem-solving skills in early childhood includes asking questions and investigating the answers through collecting, organizing, representing, and analyzing data with the goal of efficiently addressing real-world problems (Barr & Stephenson, 2011; ISTE & CSTA, 2011).

There are increasing calls for younger students to learn about data. For example, as Martinez and LaLonde (2020) report, the American Statistical Association recommends providing meaningful "data-rich learning environments" in kindergarten to prepare students for future jobs that often require the ability to use or understand data (Franklin et al., 2005). As the National Science Foundation's Data Science Working Group's report (Berman et al., 2016, p.2) states, "*it's not too extreme to say that data is changing everything*" and the report has led to data science being a new interdisciplinary field with deep connections to computational science. The report goes so far as to say that "*Data Science is increasingly crucial for the research and education community*" to address.

Many researchers and practitioners advocate for a renewed focus on DCA and suggest that it should begin early in children's formal education (English, 2010, 2011; English & Watson, 2015; NCTM, 2002). While there are no preschool specific standards for DCA, the Common Core State Standards call for K-1 students to explore concepts related to the collection, storage, visualization, and transformation of data and to draw inferences. DCA investigations directly address goals in the measurement and data strand (i.e., describe and compare measurable attributes, sort objects into categories, represent and interpret data), as well as the counting and cardinality strand (i.e., count objects, compare numbers). And localities are beginning to include DCA in their standards (e.g., New York State Prekindergarten standards), adding to the pressing need for research with preschoolers.

Research suggests that the development of mathematical knowledge and reasoning begins at a younger age than is typically acknowledged (English & Mulligan, 2013). Findings with older students suggests that rich, engaging experiences with data further develop students understanding of related mathematical concepts, foster application of mathematics in authentic venues, and develop communication skills (Stohlmann & Albarracín, 2016), all of which are part of CT. Appropriately designed educational interventions can help young children engage with complex mathematical concepts (Clements & Sarama, 2014), yet research is limited on how preschool students best learn about data.

Table 1
Comparison of Data Standards.

	K-12 Computer Science Framework	ISTE	CSTA
Data Collection	Data is collected with both computational and noncomputational tools and processes. In early grades, students learn how data about themselves, and their world is collected and used. As they progress, students learn the effects of collecting data with computational and automated tools.	The process of gathering appropriate information	*Collect and present the same data in various visual formats* The collection and use of data about the world around them is a routine part of life and influences how people live. Students could collect data on weather, such as sunny days versus rainy days, the temperature at the beginning of the school day and the end of the school day…Students could count the number of pieces of each color candy in a bag of candy…Students could create surveys of things that interest them, such as favorite foods, pets, or TV shows, and collect answers to their surveys from their peers and others. The data collected could then be organized into two or more visualizations, such as a bar graph, pie chart, or pictograph.
Data Visualization & Transformation	Data is transformed throughout the process of collection, digital representation, and analysis. In early grades, students learn how transformations can be used to simplify data. As they progress, students learn about more complex operations to discover patterns and trends and communicate them to others.	(Called Data Representation) Depicting and organizing data in appropriate graphs, charts, words, or images.	
Inference & Models	Data science is one example where computer science serves many fields. Computer science and science use data to make inferences, theories, or predictions based upon the data collected from users or simulations. In early grades, students learn about the use of data to make simple predictions. As they progress, students learn how models and simulations can be used to examine theories and understand systems and how predictions and inferences are affected by more complex and larger data sets.	(Called Data Analysis) Making sense of data, finding patterns, and drawing conclusions	*Identify and describe patterns in data visualizations, such as charts or graphs, to make predictions,* Data can be used to make inferences or predictions about the world. Students could analyze a graph or pie chart of the colors in a bag of candy or the averages for colors in multiple bags of candy, identify patterns for which colors are most and least represented, and then make predictions as to which colors will have most and least in a new bag of candy. Students could analyze graphs of temperatures taken at the beginning of the school day and end of the school day, identify the patterns of when temperatures rise and fall, and predict if they think the temperature will rise or fall at a particular time of the day based on the pattern observed.

3. A learning blueprint for data collection and analysis learning goals

To develop and test a set of developmentally appropriate problem-solving activities that integrates mathematics and CT and to ground the development of the intervention and assessment as part of an evidence-centered design approach, we developed a learning blueprint (Blinded for peer review). The goal of creating a learning blueprint was to illustrate the theoretical links between early childhood data collection and analysis mathematics learning standards and data-related computational thinking standards. In the blueprint, we draw from the literature on assessment development and specify target knowledge and skills, identify task features that make tasks easier or more difficult, and specify how knowledge is demonstrated (Mislevy & Haertel, 2006). As an anchor to the work, the learning blueprint makes these learning goals explicit, and these are the pillars upon which the problem-solving activities in this intervention were developed and, in parallel, the assessment tasks, so that the learning activities and assessment tasks align to the learning blueprint rather than to one another.

To include goals related to problem-solving with data, we examined computational thinking learning goals from an existing CT framework (K–12 Computer Skills Framework CSF, 2016), one part of which focused specifically on data science. The CSF (2016) identifies five core CT concepts: (1) computer systems, (2) networks and the Internet, (3) data and analysis, (4) algorithms and programming, and (5) impacts of computing. Specifically noting the important role that data plays in the current world and identifying teaching children to work with data as a critical goal. This framework was selected after comparing it to two other frameworks, including the International Society for Technology in Education's (ISTE) Computational Competencies and the Computer Science Teachers Association K-12 Computer Science Standards (see comparison Table 1). The K-12 CSF framework was selected due to its specificity.

The framework (K–12 CSF, 2016), breaks down the CT skills related to data and analysis into four sub-practices (data collection, storage, data visualization and transformation, and inference and models) and within each, there are specific data learning goals, which formed the basis of our overarching CT learning goals. For example, the data collection sub-practice includes understanding when data needs to be collected to answer a question and how to sort/classify data into categories. These conceptually connect to the mathematically framed learning goals from other researchers.

The mathematics learning goals we included in the learning blueprint built upon existing learning trajectories (Clements & Sarama, 2014), starting with the trajectory for data collection and analysis and incorporating related skills from other trajectories to integrate mathematical skills (counting, sorting, ordering, comparing, classifying) used in this applied context. Mathematical learning goals include an overarching learning goal, such as "*Children use mathematics (*i.e. *comparing, ordering, measurement) to compare parts of a data visualization*," into specific learning goals, such as "*children place collections in order (ex. smallest to largest)*"" and "*children can align tow objects to determine whether they are the same, one is larger ect.*" By aligning the overarching CT learning goals with overarching and specific mathematics learning goals, we created an organized representation of DCA learning goals for young children.

The resulting blueprint identified eight overarching CT learning goals; within these larger goals are seven overarching mathematics goals with 20 specific mathematics goals related to counting, sorting, ordering, comparing, and classifying, as well as organizing data, describing data, and creating visual representations. DCA thus serves as an applied context for using other mathematics content (e.g., counting, sorting, classifying, comparing) and fosters its use in the service of using data to answer a research question (Brownell, 2014). As the concentric circles of the learning blueprint unfold, an example CT goal in our blueprint states that "*Children can classify and sort data into categories based on the question,*" then the overarching mathematics goal states, "*children sort objects and use one or more attributes to solve problems,"* which leads to several specific learning goals, such as "*sort objects by one attribute*." Child assessment items were created to address these specific mathematical learning goals, measuring the proximal mathematics goals rather than the more distal CT learning goals to judge learning outcomes. That approach grounds the project within the mathematics domain while describing the overarching relationship between the mathematics and CT domains.

4. Developmental appropriateness of using technology with preschoolers

Technology can be used strategically to foster engagement with mathematics and problem-solving and is considered important to computational thinking (National Research Council, 2010). Our approach leverages a digital app—the *Preschool Data Toolbox*—designed specifically for preschool teachers to use with preschoolers. Yet, readers might wonder about the developmental appropriateness and pedagogical foundation for using technology in this way. This digital app was designed to be mediated by a teacher, rather than an app children play independently. Furthermore, it builds on research of how technology aids in collaborative learning (Lim, 2012) and socialization (Mashburn & Pianta, 2006). The tool scaffolds the investigation process, moving from stating a research question to selecting the variables and range, entering data, and interpreting the meaning of that data from a graph. This scaffolded approach within a dynamic platform allows teachers and children to manipulate data representations (e.g., convert a pictograph to a bar graph) and display types (e.g., represent data in bar or tally chart format). In our approach, the tool streamlines the collection and exhibition of data, includes tools to make comparison of graphs an active endeavor, and facilitates discussions about data and the use of data to answer research questions.

Based on prior research of early math learning trajectories, young children begin to engage in investigations by using the attributes of concrete objects to count them, classify objects by categories, and sort into groups as stepping-stones toward solving problems with data (Clements & Sarama, 2009). Starting with a research question that is developmentally appropriate for young children, such as "*How do most children get to school in the morning? What color shirt do most children wear?,*" adults can support preschool children in answering this question through the collection of data (Brownell, 2014).

However, it is critical to consider the cognitive load involved in using data to answer questions. Technology can alleviate this cognitive load by leading children through the investigation process and recording relevant information in organized ways for later reference. Technology also provides options for how to represent the data in a way that children can interpret, especially when they return to it at a later time. Moreover, technology can support comparisons between data within various categories (Brownell, 2014). With these affordances in mind, the *Preschool Data Toolbox* app set out to provide the necessary scaffolds and adult support to foster DCA engagement and learning in preschoolers.

5. Context of preschool teacher preparedness to teach DCA

Preschools within the United States are typically separate from the K-12 public education system, and teacher training and certification differs across states. While teacher educational experience and training differ, recent research suggests that the relationship between teacher training and indicators of classroom quality is not straightforward (Lin & Magnuson, 2018; Nocita et al., 2020). Rather, research suggests that well implemented preschool mathematics interventions lead to positive learning outcomes (Clements & Sarama, 2008); yet the focus on training preschool teachers to teach mathematics to preschoolers and the emphasis on doing so is relatively new (Hachey, 2013). The methods and instructional approaches also differ from those in other countries; for example, a comparison with China revealed that preschool mathematics teachers are less intentional in their mathematics instruction and that curriculum is broader (Li, Chi, DeBay & Baroody, 2015). Preschool educators often lack the content and pedagogical skills to ensure positive mathematical outcomes for preschoolers (Sheridan et al., 2019). Access to high quality professional learning experiences for teachers is growing and more available than in the past (Brenneman, Lange, & Nayfeld, 2018).

The preparation of preschool teachers to teach mathematics has improved dramatically, yet preschool teachers' knowledge of data collection and analysis (Blinded for peer review) and computational thinking is in its early stages (Wang, Choi, Benson, Eggleston & Weber, 2020). There is not widespread access to the training that teachers need to engage preschoolers in computational thinking or DCA; yet detailed professional development and thoughtful use of technology can result in positive learning experiences (Lavigne, Orr, Wolsky, Brunner & Wright, 2021; Lin, Chien, Hsiao, Hsia & Chao, 2020; Papadakis, 2022). To successfully support early learners to problem-solve with data and use technology to support modeling with data, researchers need to further develop and explore how the thoughtful use of computational skillsets and digital technologies can deepen children's learning of mathematics.

6. Materials and methods

As part of an iterative, design-based implementation research approach (DBIR; Clements, 2007; Cobb, Confrey, diSessa, Lehrer & Schauble, 2003), this study is a design-based study using a mixed-methods approach. To start, a learning blueprint was developed to articulate specific learning goals and a conjecture map communicated the theories underlying the intervention's development and how it was hypothesized to lead to the documented learning outcomes (Sandoval, 2014).

Research questions follow:

1. How did teachers and students engage with and use the DCA intervention (investigations and digital app)? [Data source: teacher surveys and interviews, classroom observations]
2. Did teachers perceive improved learning (i.e., in DCA knowledge specifically, and in mathematics and CT generally) in their children as a result of engaging with the intervention? [Data sources: teacher interviews]
3. Did children's mathematics and data collection and analysis knowledge and skills increase from the beginning to end of the intervention (as measured by assessment tasks)? [Data sources: child assessment]
4. What affordances of the Preschool Toolbox app supported preschool teachers when engaging students in learning activities? [Data source: teacher surveys and interviews, classroom observations]
5. What challenges did teachers experience when using the app to engage students in learning activities? [Data source: teacher surveys and interviews, classroom observations]

6.1. Recruitment and participants

The study took place within public preschool classrooms located throughout Rhode Island. Thirteen preschool teachers were recruited from ten different classrooms across six schools. The study took place within public preschool classrooms located throughout Rhode Island.

Teachers from ten different classrooms across six schools were recruited. Two of these ten classrooms were recruited as comparison classrooms and two other classrooms were moved to the comparison group after the teachers attended the first professional development session, as the teachers could not do the intervention activities, but child pre-assessments had already been completed. Comparison classrooms only participated in child assessments and did not implement the intervention. Three of the ten participating classrooms had pairs of co-teachers that shared the study's planning and professional development activities and shared teaching responsibilities (n = 13 teachers; Treatment= 8; Comparison teachers=5). Thus, the final study sample included a total of ten classrooms, six of which implemented the intervention and four of which continued with business-as-usual teaching. *Teacher Participants*. In the six intervention classrooms, eight teachers participated in the study and completed the teacher interview and survey. These teachers' years of teaching ranged from 1 to 20 years with a mean of 7.8 years. All teachers were women and most identified as White (n = 7), while one teacher identified as Hispanic. The highest level of teacher education varied: associate's degree (n = 1), bachelor's degree (n = 6), and graduate degree (n = 1).

Table 2
Description of Intervention Activities.

Investigations	Description
What Do We Wear?	Children sort themselves by their own clothing attributes and then sort clothing items from their classroom's dress up area (or cards with illustrations of clothing on them) before graphing and discussing the data.
Animal Data Shuffle	Children create a series of graphs focused on attributes of animals and people. First, they read a book (*Five Creatures* by Emily Jenkins) and create pictographs based on character attributes. Then they use animal cards to sort how the animals move and the number of legs they have, creating pictographs, body graphs, and bar graphs.
The Hungry Caterpillar	Children create a series of graphs focused on how many pieces of food the caterpillar in *The Very Hungry Caterpillar* by Eric Carle ate each day. Then children vote for their favorite fruits and vegetables, make graphs of each, and compare and discuss them.
Our Feelings Freeze	Children create three graphs about their feelings at different time points, create graphs, and compare the graphs to discuss what the data shows.
Frame It	Children predict, sort, and create graphs of the different objects they see inside a frame within their classroom and outside.
Measure with ME	Children use three units of measurement (e.g., their bodies with arms outstretched, their bodies with arms by their sides, and their shoes) to measure an area of the classroom, such as the circle time rug. They then create a graph to compare their measurements.
Create-Your-Own Investigation #1 & #2	Teachers and children generate their own research questions related to other activities in their curriculum or the children's interests. They decide on relevant categories, collect data, create graphs, and engage in discussion.
Design a Data Story	Teachers and children pick an investigation theme that includes several related research questions, then collect, graph, and describe data. The app helps them create a storybook using a template that annotates their investigation process with text about what they asked, found, and thought.

Child Participants. In each participating classroom, children in preschool classrooms who spoke English were invited to participate. In total, 85 children (56% female) participated and completed both the pre-intervention assessment and the post-intervention assessment. Children ranged in age from 38.8 to 66.6 months, with an average age of 58.7 months (SD = 6.04). Teachers described the demographics of their school population as being mixed income ($n = 3$) or low-income ($n = 5$).

6.2. Intervention

The intervention consisted of nine curricular investigations with an integrated digital app (the *Preschool Data Toolbox*) that scaffolded the preschool DCA process and offered an applied problem-solving context for using mathematical and CT knowledge and skills. Investigations included pre-written investigations, teacher-generated investigations, and a theme-based investigation that led to the creation of a short, narrative story about the data (See Table 2 below). The investigations were hands-on and play-based and involved identifying research questions, collecting data, creating simple representations, and discussing and interpreting charts and graphs to answer questions. The app scaffolded this process by supporting teachers as they moved through specific DCA steps (i.e., collecting, representing, and interpreting data). Teachers can access lesson plans, background information about DCA, and videos to support implementation both within the app and through an online Teachers' Guide (https://first8studios.org/gracieandfriends/guide/dca/).

The *Preschool Data Toolbox* app helps teachers set up the investigations by selecting existing or inputting new research questions, selecting variable icons or taking photographs to represent new variables, select the range for the graph, and includes a simple interface to enter data with plus and minus symbols (Fig. 1). Once data is entered, teachers and children can use the analysis page (Fig. 2) to draw on the screen (Fig. 3), view discussion prompts (Fig. 3), sort the data (e.g. ascending, descending, and by hand; Fig. 4), and transform the data from a pictograph to a series of stacked boxes (Fig. 5) or one large bar for each variable on the graph.

Investigations typically include three to five distinct data-related activities and use hands-on materials, physical movement, and/or books in addition to the use of the tablet app. For example, the *Animal Data Shuffle* investigation begins with reading a book called *The Five Creatures* by Emily Jenkins. The book includes five characters (three humans, two cats) that have similar and different features and attributes, with each page highlighting a characteristic (e.g. orange or gray hair; human or cat; eats fish or does not eat fish). The same five creatures can be grouped by different attributes to create data displays with some similarities and some differences. Teachers read this story and then create a series of graphs to compare the characters in a variety of ways. The teacher helps the children look at the relevant page of the story, create a graph to represent how the characters are sorted, and have a class discussion about

Fig. 1. Preschool Data Toolbox Data Entry Page.

what the graph represents (e.g. How many creatures are in each group? Which group has the most/least/same number of creatures? Where on the graph do you see this information?).

The next day, the teachers give each child a card with a picture of a different animal on it and the class plays a "pick your corner" game to sort themselves into groups based on the attribute of how many legs their animal has (0, 2, or 4 legs). After children move themselves to one of three corners based on the number of legs their animal has, they count how many animals are in each group and enter that data to create a graph. Next, the children re-sort their animal/themselves based on a new attribute, the way their animal moves (run, hop, slither, or fly), and they move into one of four corners of the rug. Children can enter the data and create a data display. Teachers then hold a discussion about the dif-

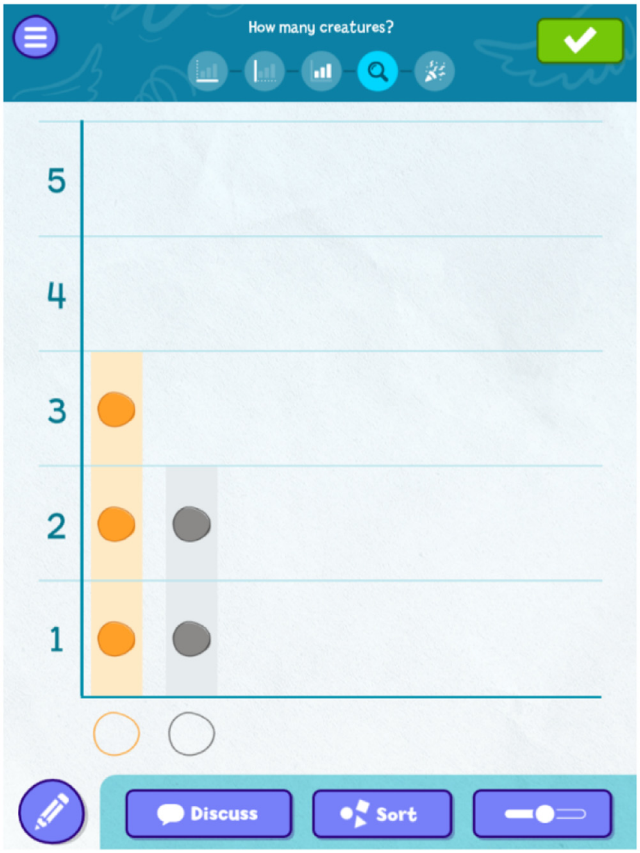

Fig. 2. Preschool Data Toolbox Analysis Page.

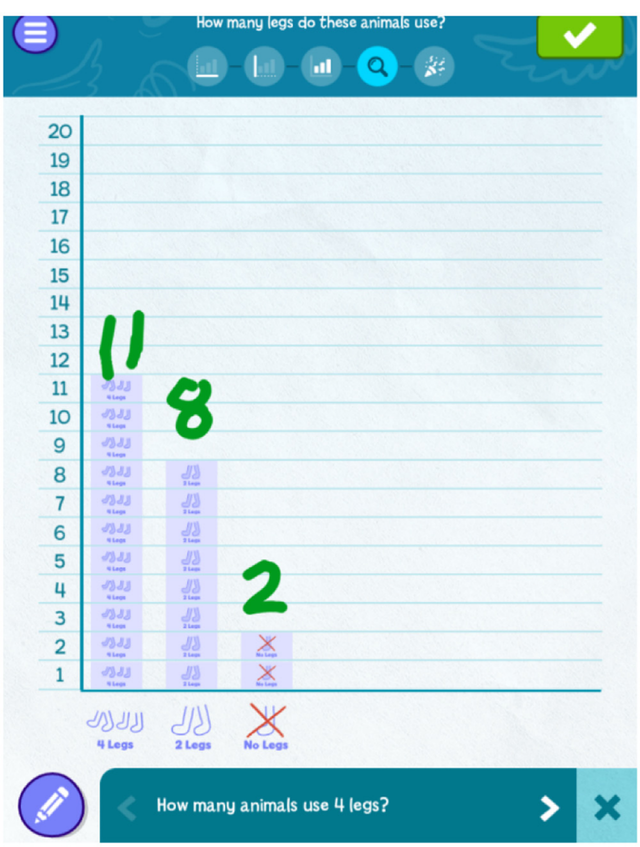

Fig. 3. Preschool Data Toolbox Drawing Feature and Data Talk Prompts.

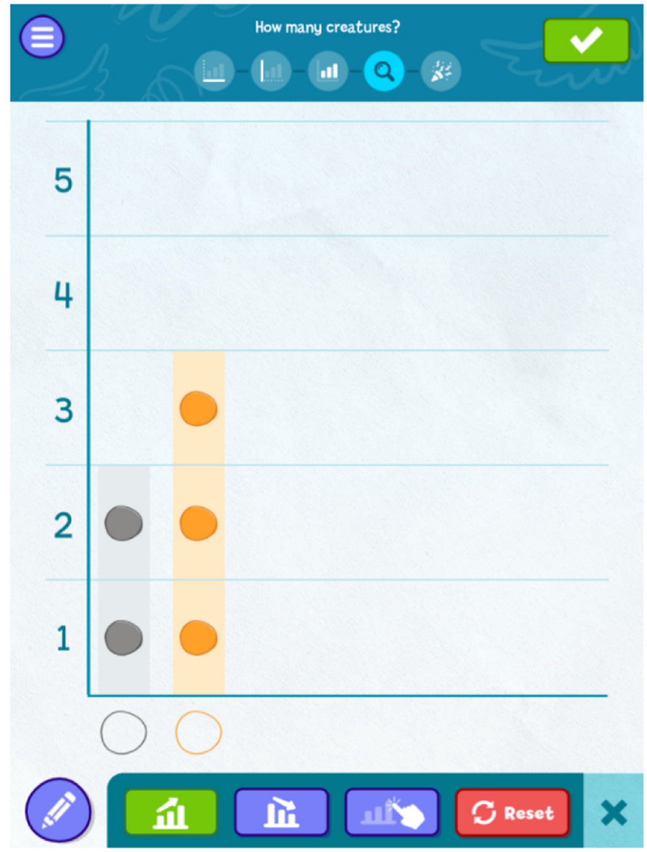

Fig. 4. Preschool Data Toolbox Sorting Feature.

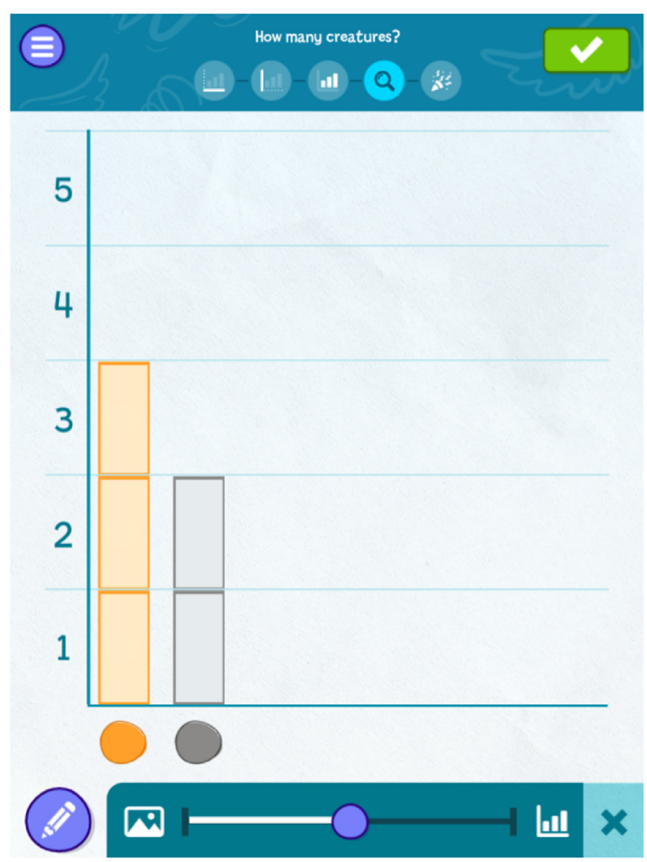

Fig. 5. Preschool Data Toolbox Sorting Feature.

ferent data displays. During the discussion, the class looks at each graph individually to answer questions about how the animals are sorted, how many animals are in each group, and which group has the most/least. Children are encouraged to point to where on the graph they find these answers or use the "drawing tool" to show that information to the data display (such as category counts).

In other activities, children are challenged to compare data from two different data visualizations. For example, in the *Our Feelings Freeze* investigation children are asked how they feel at the beginning and end of the day. The teacher and children enter the data and create two data displays, comparing the change in feelings by looking at both graphs together and discussing why feelings might be different at different times of the day.

In the *Create Your Own* investigations, teachers and children can invent new investigations based on their own interests, often linking data collection to other things the class is learning about during the day. For example, teachers can pose a "question of the day" (e.g. "Which do you like more?"), graph data from a book or event (e.g. "How many children used the slide today?"), or take inventory of a set of objects (e.g. "How many red vs blue bears in this bin?").

6.3. Professional development

Teachers attended three professional development sessions that covered the goals of the project, expectations and requirements of the study, and each curricular investigation in detail, allowing teachers to ask questions and share feedback on completed investigations. Each session included short videos that described and modeled the process of using the app during the investigations, and these videos were made available to teachers after each session. The professional development also included time for teachers to brainstorm ideas for creating their own investigations and designing their data stories based on the questions and interests that had been arising from their students. The study offered three opportunities for teachers to attend "office hours" to troubleshoot issues and ask questions over the course of the study, and teachers were encouraged to email or call us at any time.

6.4. Instruments and analysis

Classroom Activity Observation. Classroom implementation was video recorded by teachers and coded by researchers to examine the DCA processes that occurred, including math content, child engagement, use of the app, and data discussions, as well as CT specific practices, such as visualization and interpretation. Challenges to classroom implementation, as well as the types of supports that were needed for teachers and children to accomplish their DCA goals, were also identified.

Teacher Interview and Survey. At the end of the study, all intervention teachers completed a one-hour interview and an online survey. The semi-structured interview and survey protocols included both open- and closed-ended questions to elicit feedback on the app, developmental appropriateness of the curricular investigations, clarity of the investigations' lesson plans, perceptions of how well each investigation met its learning goals, and teachers' overall experiences participating in the study.

Child Assessment. A one-on-one, direct assessment of preschoolers' skills in DCA was developed by the research team, then revised based on data from the first pilot study, and finally administered by the research team via videoconferencing for this study. Specifically, teachers set up a tablet with video conferencing software on it, so that researchers could meet one-on-one with each child. It presented stimuli using an animated PowerPoint presentation and asked children to respond verbally by either choosing an image or providing brief responses to open-ended questions. Assessment items were tied to relevant learning goals in the learning blueprint related to DCA (e.g., describing parts of data visualizations). For example, items asked children to compare groups (e.g. most/least/same) and items (e.g. length), sort groups of items from smallest to largest, sort (e.g. by color, size, shape, category), and answer questions based on simple, graphs and tally charts. The assessment consisted of 34 items that took approximately 20 min to administer and was almost always completed in one testing session. All items (or subparts of items, in some cases) were scored as correct (1) or incorrect (0). Items had a good range of difficulty, ranging from 0.15 to 0.92 at post-intervention with a mean of 0.57 (SD = 0.23). Scale scores were calculated by averaging scores across items to create a proportion correct. The scale had good internal reliability at both pre- and post-intervention (Cronbach's alpha of 0.86 and 0.89).

7. Results

7.1. Participant engagement with the intervention

7.1.1. Summary of typical use

Classroom observations indicated that teachers engaged children in both the hands-on and digital (app) aspects of the intervention. Implementation occurred primarily in small student groups during morning and afternoon learning stations or "center" time. However, teachers' interview data indicated that when they were "off camera," they had more flexibility to run or repeat activities (e.g., storybook reading) with their full class without the constraint of avoiding filming non-consented children. Notably, regarding group size and child engagement, variations were observed between the use of the hands-on activities and the app. For example, when sorting tangible data, such as animal picture cards (Anima Data Shuffle) or toy fruits (the Hungry Caterpillar), or when creating physical graphs (e.g., tally graphs on a whiteboard or object graphs on the floor or table), larger groups of children were able to participate due to the greater availability of materials and larger workspaces. However, because teachers were provided with only one tablet, use of the app—whether for data entry, graph annotation or customization, or display and interpretation of completed graphs—typically could not accommodate more than three children at a time. The teachers recognized this limitation as the intervention progressed and adjusted their app usage to focus on two to three children at a time, typically running multiple short app graphing sessions.

7.1.2. Ease of integration into preschool classrooms

In survey responses (see Table 3), all teachers agreed that they could easily fit the investigations into their math curriculum. Most teachers agreed that the investigations fit into the regular classroom schedule and that lesson plans were easy to follow. Likewise, most teachers agreed

Table 3
Teachers Ratings of Integration Aspects.

Statement	Strongly Agree	Agree	Neither agree nor disagree	Disagree	Strongly Disagree
I can easily fit the investigations into my curriculum.	4	4			
It is easy to fit the investigations into my regular classroom schedule.	2	5	1		
The lesson plans are easy to follow.	4	2	2		
The investigations fit my students' current math skills.	1	5	1	1	
The investigations supported my students in learning new math skills.	5	2	1		

Table 4
Developmental Appropriateness of Investigations ($N = 8$).

	Strongly agree	Agree	Neither agree nor disagree	Disagree	Strongly disagree
What Do We Wear?	3	5			
Animal Data Shuffle	4	4			
The Hungry Caterpillar	3	4	1		
Our Feelings Freeze	5	3			
Frame It	5	3			
Measure with ME	6	2			
Create Your Own	5	3			
Design a Data Story	4	4			

that the investigations fit their student's current math skills and supported their students in learning new math skills.

In interviews, teachers responded that their classrooms had positive, fun, and engaging experiences, and that they plan to incorporate DCA into their future math and non-math lessons. The teachers especially valued the versatility of DCA and the opportunity it gave children to take charge of their own learning. Their responses frequently noted ways that problem-solving with data and CT are cross-cutting and were becoming a natural part of the children's problem-solving repertoire. For example, teachers stated the following:

> *"That's where it was fun. You could implement other things into the app. So it was everything. It was social studies. It was self-awareness. It was science and literature and the math, which is the most important part. So I thought it was great to have everything in one app, and it was just so versatile that it's user friendly, and I really had a blast."*

> *"It was funny how some of my lessons that I planned before reading the investigations overlapped. So a lot of graphing. I love graphing with them, and so do they. So we did a lot of that."*

7.1.3. Developmental appropriateness of investigations

For each investigation, teachers were asked to rate the degree to which they agreed that the investigation was developmentally appropriate (Table 4). All investigations received either a "strongly agree" or "agree" rating from all teachers, with the exception of one "neither agree or disagree" for Hungry Caterpillar, which other data suggest was a more complicated investigation and subsequently has been revised.

7.1.4. Teacher ratings

Using a Likert scale (1–5), teachers were asked to rate a series of statements intended to determine the degree to which teacher comfort and preparedness, as well as their assessment of the appropriateness of intervention activities for preschoolers, changed from the beginning to the end of the study. Teacher's mean ratings from the beginning to the end of the intervention increased on all indicators (see Table 5) except for feeling nervous about facilitating DCA activities, which understandably went down. Change scores were also calculated (Table 6), showing the same pattern; however, the sample size was small ($n = 8$) and these means had wide standard deviations. The overall pattern does suggest that teachers increased in their understanding of DCA, felt more comfortable and less nervous facilitating and engaging in DCA with young children, and were more comfortable with using technology in their teaching. Teachers also increased on measures related to their beliefs about children's readiness and capacity for engaging in DCA activities, such as the extent to which they thought it was developmentally ap-

Table 5
Teacher Indicators ($N = 8$).

Time	Mean	Very High (5)	High (4)	Neither (3)	Low (2)	Very Low (1)
Understand how to include data collection and analysis in my lesson plans.						
Before	2.50	1		4	1	2
After	4.25	2	6			
Feel nervous about facilitating data collection and analysis activities						
Before	2.75	1		4	3	
After	2.25	1	1		3	3
Feel comfortable engaging in data collection and analysis with young children						
Before	2.63	1		3	4	
After	4.25	2	6			
Feel comfortable using technology in your teaching						
Before	3.00	1		6	1	
After	4.38	3	5			
Think data collection and analysis is developmentally appropriate for my students						
Before	2.62	1		3	4	
After	4.13	1	7			
Think children would be interested in graphing activities						
Before	2.75	1		4	3	
After	4.00	2	5		1	
Think children can do graphing activities						
Before	2.88	1		5	2	
After	4.00	8				

Table 6
Mean Changes in Ratings (N = 8).

Statement	Mean Change in Rating	Standard Deviation
Understand how to include data collection and analysis in my lesson plans.	1.75	1.16
Feel nervous about facilitating data collection and analysis activities.	1.50	0.53
Feel comfortable engaging in data collection and analysis with young children.	−0.50	1.93
Feel comfortable using technology in your teaching.	1.63	0.74
Think data collection and analysis is developmentally appropriate for my students.	1.25	1.28
Think children would be interested in graphing activities.	1.13	0.64
Think children can do graphing activities.	1.38	0.74

propriate and the extent to which they anticipated children would be interested in and capable of engaging in graphing activities.

Specifically, teachers were asked to rate their comfort levels for facilitating DCA lessons both before and after participating in the study. Beforehand, 50% (n = 4) of teachers responded that they felt low comfort with DCA—and in some cases, with early math in general.

"Math has never really been my strong suit, so it's definitely not something I would always gravitate towards. So I feel like the app was a great tool to include math in our lesson plans every week."

However, all teachers (n = 8) indicated that their post-intervention comfort levels with DCA were high and that they felt more knowledgeable about early mathematics learning in general.

"I definitely feel a lot more confident in it. I know how to approach it better, especially with the preschool age, because I used to student teach first and second grade, so it was totally different, and this was very hands on. The kids really enjoyed it."

"It was really one of the first times I've done in-depth graphs with the children. So I think it was a great experience. Not only for the kids, [but] for me too."

Using the DCA app also increased teachers' comfort levels with using technology in their classrooms. Most teachers (n = 7) reported that, prior to the study, their comfort with using technology was either "low" or "neither low nor high." However, all teachers (n = 8) increased to a reported "high" or "very high" comfort level post-intervention, and in their interviews, the teachers noted that the app provided a model for using technology in an educational way. The teachers contrasted this study's app with the educational apps currently on the market, which they reported as being not particularly child, teacher, or school friendly or appropriate.

"It gave them a visual representation of what we were [doing]. They were able to contribute. So they were able to enter the data in. They love using the iPad, and being able to put the plus sign or the negative sign [in] or doing the tools. So it gave them a sense of empowerment I would say."

7.1.5. Preparation and pacing

For each investigation, teachers were asked how easy it was to prepare. Teachers responded for each of the pre-made investigations and, in general, agreed that it was easy to prepare (see Table 7). Animal Data Shuffle challenges related to creating body graphs with small numbers of children due to pandemic-related absences. Hungry Caterpillar challenges related to the many representations created, and Frame It challenges related to finding objects outdoors and accurately counting those (e.g., how to count blades of grass within the frame). Revisions of the investigations centered on addressing these concerns.

For each investigation, teachers were asked about the pacing of the activity, and in most cases, six to eight teachers agreed that the suggested pacing was "about right." The exception to this was the Hungry Caterpillar investigation to which most teachers (n = 5) found it took longer than the 2–3 days suggested. In response, the investigation was slightly shortened and the suggested time slightly increased.

7.1.6. Teacher and student roles

Based on activity observations, the intervention was teacher-led, with children taking on larger and more independent roles as their classrooms progressed through the investigations and as they became more familiar with the app, DCA vocabulary, and graphing tasks. Across the investigations, teachers introduced research questions and managed hands-on materials, set up graph structures (e.g., x-axis categories and category labels, y-axis range), and facilitated group discussions about graphed data. On the other hand, children's roles varied across investigations, with their ability to sort materials, add data to graphs, and interpret graphed data ranging from being highly scaffolded in the earlier investigations (e.g., What Do We Wear?) to being increasingly child-led in later investigations (e.g., Frame It). For example, in some cases teachers selected all these settings for the graph and entered the day, while in other cases the teacher handed the child(ren) the tablet so that they could make these selections and data entry directly.

These trends were observed consistently across both the hands-on activities and use of the app, with children's interactions with the app (e.g., holding the tablet, selecting category icons, adding data to graphs, and using the app's graph interpretation tools) increasing over time. For example, while conducting a *Create Your Own* investigation, one child held the tablet and went to each child in the class to ask them a question about what they liked best and enter their vote in the graph. Notably, in one classroom, the teacher set up a special science center station and placed the tablet and a set of science manipulates (e.g., sorting bugs) on a table for children to categorize, sort, and graph independently. In Table 8, we describe the observed teacher and child behaviors during the *Hungry Caterpillar* investigation (Table 8) and task roles (Table 9) and demonstrations of DCA skills (Table 10) during the *Our Feelings Freeze* investigation, which was implemented approximately halfway through the intervention.

Table 7
Ease of Preparation (N = 8).

	Strongly agree	Agree	Neither agree nor disagree	Disagree	Strongly disagree
What Do We Wear?	3	5			
Animal Data Shuffle	4	3	1		
The Hungry Caterpillar	4	3	1		
Our Feelings Freeze	5	3			
Frame It	4	3		1	
Measure with ME	5	1	1		

Table 8
Observed Data Collection and Analysis Behaviors (example: Hungry Caterpillar Investigation).

Evidence Observed
Fruit in the form of picture cards and plastic fruits was sorted by day of the week (M-F and then Sat-Sun).
Using plastic fruit and picture cards, children created object graphs and pictographs on the floor to represent (a) the food the caterpillar ate and (b) their favorite fruits and vegetables.
Object graphs and pictographs were created on the floor with hands-on materials, pictographs were created in the app, and tally graphs were drawn on chart paper.
Children looked at the resulting graphs and answered questions based on that graph (e.g. determining how many, which was more/less/same, most/least/ equal).
Looking at the data visualization (hands-on, in the app or on paper), children counted how many in each graph category (e.g. how many fruit on Monday) and answered quantitative
questions that included: how many, how many in all, how many more, and how could the categories be made equal.
Children discussed patterns in the data represented visually (e.g., the number of foods eaten Monday through Friday increased by one each day) and made predictions about the number of foods eaten on Sat-Sun.

Table 9
Teacher and Child Roles during the Our Feelings Freeze Investigation.

DCA Investigation Step	Teacher Role	Child Role
Data collection	Introduce research questions and activity materials	• Select emoji face cards to represent feelings • Make predictions about feelings • Strike silly poses
Visualization and transformation	Graph setup and introduction	• Add tally marks to tally graphs (classroom whiteboard) • Add cards to pictographs on the floor or table • Count how many in each category
Inference and models	Facilitate data talk	• Answer numeric questions: ○ How many? ○ How many altogether? ○ Which category has most, least, same? • Answer open-ended questions: ○ What is a prediction? ○ What do you see in this graph? ○ Why is sorting data into ascending or descending order helpful?
App use	• Graph setup and introduction (e.g., x-axis categories, y-axis range) • Use of app tools (e.g., annotation tool, sorting tool)	• Add data to graphs by tapping the “+” button for each graph category • Count how many in each category • With teacher scaffolding, use the annotation tool (to label graph columns with numerals), the sorting tool, and the slider tool *Note: In some classrooms, children took turns interacting with the app (*e.g., *teachers called children up one at a time to enter their feelings data). In other classrooms, teachers called on one child to use the app, entering all data while other children looked on.*

Table 10
DCA during the Our Feelings Freeze Investigation.

DCA skills	Evidence observed
Sorting	Children identified their “in the moment” feelings, selected a corresponding emoji face card, and sorted the cards into five categories: tired, happy, sad, silly, and angry.
Data representation	Children used the emoji cards to represent data in pictographs on the floor and tally marks to represent data in tally graphs on their classroom whiteboard.
Create data visualization	Children created tally graphs on whiteboards, physical pictographs using emoji cards, and pictographs and bar graphs in the app.
Describe graphed data	Teachers discussed with children their graph’s x-axis categories, y-axis range, and data points.
Quantify graphed data	Children answered questions about how many were in each graphed category and which categories had the most, least, and same. In the app, teachers used the sorting tool to arrange their graphed data by ascending and descending order, the slider tool to transition between pictograph and bar graph formats, and the drawing tool to label graph columns with numerals.
Interpret results	Teachers asked children to examine graphs and answer numeric questions about how many, most, least, and same. They also asked open-ended questions, including Why do you think most children feel happy or tired in the morning? How might feelings change later in the day?

7.1.7. Engagement with DCA content

During classroom observations, evidence of teacher-child engagement in each CT-focused mathematics domain was observed, with teachers engaging children in sorting in 92% of observations, data representation in 98% of observations, creating visualizations in 88% of observations, describing graphed data in 93% of observations, quantifying graphed data in 93% of observations, and interpreting graphs in 84% of observations. Notably, 95% of observations also evidenced teachers engaging in mathematical dialog with their students, which typically highlighted and deepened understanding of all the CT practices embedded in the DCA content.

Yet variations within these trends were found. For example, teachers and children arranged their graphed categories in ascending or descending order—a sorting and quantifying graphed data skill—in only 22% of observations. And describing different parts of graphs (e.g., the x- and y-axes), a sub-domain of the “describe graphed data” skill, occurred in only 43% of observations. Differences were also found when examining mathematics trends by individual investigation. Although the majority (n = 5) of investigations demonstrated a 90% or higher engagement level in mathematics content, three investigations were found to be relatively low: Frame It (68% of observations evidenced engagement in mathematical content), Create Your Own Investigation (86%), and Design Your Own Data Story (76%). These three investigations were the final lessons in the curricular series and gave teachers the most autonomy to design their investigation activities and integrate mathematics content. For instance, in Frame It, teachers chose set(s) of materials for their students to sort and the sorting attribute (e.g., color, shape, or item type) to sort by. Similarly, in Create Your Own Investigation, teachers

Table 11
Percentage of Teachers Reporting Learning Goal Met.

Investigation	Counting	Sorting	Comparing	Classifying	Collecting Data	Describing Data	Creating Visual Representation	Organize Data	Interpret Data
What Do We Wear?	100	100	100	100	87.5	87.5	87.5	87.5	87.5
Animal Data Shuffle	100	100	100	100	100	100	100	100	100
The Hungry Caterpillar	100	100	100	100	87.5	87.5	87.5	100	100
Our Feelings Freeze	100	100	100	100	100	100	100	100	100
Frame It	100	100	87.5	100	100	87.5	87.5	87.5	87.5
Measure with Me	100	87.5	100	100	100	100	100	100	100
Create Your Own	100	100	100	100	100	100	100	100	100
Design a Data Story	100	100	100	100	100	100	100	100	87.5

chose the research question(s) to be investigated, the data to be collected, the graphs to be created, and the questions about the data that would undergird their analysis and interpretation discussion. Teachers' interview responses and their classroom observation data indicated that they varied in their comfort levels with these design elements, highlighting the need for robust teacher guidance and support to be integrated into the DCA curriculum (i.e., a teacher's guide and lesson plans).

7.2. Teacher perceptions of student learning

Teachers reported that overall, the investigations met the intended CT and math learning goals. Each investigation was aligned with some or all of the nine identified learning goals. Survey findings indicated that teachers felt each investigation met all or most of the stated learning goals (see Table 11).

Teachers reported that engagement with the intervention, and with the app in particular, helped increase preschooler's exposure to and engagement with mathematics and CT throughout the day. In interviews, teachers elaborated on how using the app helped the children see and talk about DCA more throughout their day.

Teachers reported that children's knowledge of DCA improved because of the intervention. In interviews, teachers described how the activities and the opportunity to interact with the app provided new and exciting ways for the children to engage in data collection, analysis, and discussion of data and the resulting growth in children's knowledge. Several teachers mentioned that, by the end of the project, the children did not need as much scaffolding or direction to engage in the problem-solving with data steps; meaning that the teacher could pose a research question (or have children come up with their own), and the children knew how to approach the question, collect data, and reach a conclusion.

> *"The students are going around and asking questions and getting answers, and they have the ability to look at the data that they collected. And if you were to say, well, what are you learning today or what did you ask, they're able to use the visuals and explain it themselves rather than looking at a board and seeing words that they might not be able to read. They understand colors. They understand shapes. They understand pictures. Those are symbols that have meaning to them. So, they're able to do it on their own. They loved being data scientists and taking on that role."*

7.3. Child learning outcomes

The assessment consisted of 34 items that took approximately 20 min to administer. Items had a good range of difficulty, ranging from 0.15 to 0.92 at post-intervention with a mean of 0.57 (SD = 0.23). Scale scores were calculated by averaging scores across items to create a proportion correct. The scale had good internal reliability at both pre- and post-intervention (Cronbach's alpha of 0.86 and 0.89).

Children from the 10 participating classrooms completed the assessment before the intervention (March-April) and after (May-June). An average of 8.5 children from each classroom participated in assessments (SD = 2.7). In total, 85 children completed both the pre-intervention assessment and the post-intervention assessment. Children ranged in age from 38.8 to 66.6 months, with an average age of 58.7 months (SD = 6.04). Based on ANOVA, no significant differences were detected in pre-intervention scores between classrooms that originally agreed to participate in the intervention ($n = 8$) and those that were recruited as comparison classrooms ($n = 2$), $F(83) = 0.914$, $p = .342$. Furthermore, no significant differences were detected in pre-intervention scores between classrooms that completed the full intervention ($n = 6$) and those that dropped from the intervention ($n = 2$), $F(70) = 0.943$, $p = .335$. Because this was a design-based pilot study, and classrooms were not randomly assigned to condition, classrooms that dropped from the intervention were treated as comparison classrooms in analyses.

Intervention effects on post-intervention scores were tested using a two-level hierarchical linear model (HLM, Version 7.03) to account for the nested structure of the data, or the shared variance in children's scores within classrooms. An unconditional model indicated that 24% of variance in scores was attributable to classroom-level differences. Pre-intervention scores were included as a covariate at the child level, and treatment condition was included as a predictor at the classroom level. Children in classrooms that completed the full intervention had significantly higher scores at post-intervention compared to children in classrooms that did not complete the full intervention, controlling for pre-intervention scores, $B(SE) = 0.11(0.04)$, $t(8) = 2.89$, $p = .02$. This means that, on average, children who participated in the intervention answered correctly on 11% more items than children who did not participate. Excluding the two classrooms that dropped from the intervention, children in classrooms that completed the full intervention had significantly higher scores at post-intervention compared to children in comparison classrooms, controlling for pre-intervention scores, $B(SE) = 0.13(0.05)$, $t(6) = 2.48$, $p = .048$.

7.4. Digital app affordances

The app supported teachers by increasing their comfort levels with DCA activities. Teachers noted in their interviews that because DCA was a new topic for many of them, the app provided a scaffolded way to learn and practice DCA processes. They also felt that their app graphs looked clearer and more appealing than many of the physical graphs they typically created (e.g., on chart paper and whiteboards), and these improvements ultimately led to higher-quality class discussions about graphed data.

Classroom observation data supported the teachers' survey and interview findings, with teachers becoming increasingly comfortable and confident using the app over time. They also appeared eager to have their students engage directly with the app, with some teachers encouraging individual or partnered children to be primary users during activities. In these instances, teachers tended to have children transfer existing non-app graphs (e.g., tally charts on the whiteboard, pictographs of emoji cards on the floor) into the app or dictated data to be entered into the app (e.g., "now add three happy"). In later investigations, even when teachers controlled the app, they typically still involved the children in its use by having them provide the graphing steps (e.g., "Which categories do I need to add? Which range?").

Table 12
Perceived Value of Potential New Features and Tools (N = 8).

	Very helpful	Somewhat helpful	Only a little helpful	Not at all helpful
Ability to change range for the y-axis	5	3		
Ability to add labels to the categories you choose for the x-axis	8			
Ability to print lesson plans from app	7	1		
Ability to change from pictograph to bar graph in Create Your Own investigation**	7	1		
Ability to change from pictograph to tally graph	6	1	1	
Photos of example graphs in the lesson plans	6	2		
Include example research questions for the Create Your Own investigation	6	1	1	

7.4.1. Navigation

On a teacher survey, navigation through the pre-existing activities (i.e., investigations 1–6) was rated as “very easy” (n = 3) and “somewhat easy” (n = 5); the Create Your Own activities were rated as “very easy” (n = 4) and “somewhat easy” (n = 4); and Design a Data Story activities were rated as “very easy” (n = 2), “somewhat easy” (n = 3), and “somewhat difficult” (n = 3). In response to navigation challenges with the Design a Data Story portion of the app, the app design was changed in the subsequent version of the app.

In response to questions about specific features, teachers noted that the sorting and drawing features were frequently used (n = 7); however, the class data visualization discussion prompts were used less frequently (n = 3), with many teachers choosing to use the printed discussion questions rather than those on the screen. This led to design changes for the prompts. Likewise, teachers (n = 6) reported that they would like the drawings on the screen to remain present when using other features, such as the discussion prompts, so these changes were included during app revision.

Teachers were also asked about the value of new suggested features for the app (see Table 12). Several of these options were prioritized during app revisions, such as the ability to change the range of the y-axis, print lessons, and integrate photos of sample graphs. Other features were not implemented due to various design and resource limitations. For example, adding labels to the categories on the x-axis was not implemented because of limited space on the screen. In addition, revisions addressed highlighting and increasing the ease of use of existing features, such as the status bar at the top of the screen, which seemed to go unnoticed. For example, half of the teachers either did not report it helpful (n = 1) or did not notice the feature (n = 3).

7.5. Digital app challenges

During their interviews, teachers were asked to describe any challenges they experienced when using the app. Several teachers noted that implementation became difficult when larger groups of children tried to engage with the app at once, given the tablet’s limited size. As such, the teachers tended to limit interactions with the app to small groups of children—a format that the teachers felt was ideal for all participants to be able to see the app; play an active role in the graphing process (e.g., each child having a turn entering data); and answer questions. Future implementation may use a projector to allow more children to see the contents of the screen.

Teachers also indicated that completing as much graph preparation in advance as possible, including having children’s “jobs” already assigned (e.g., one child assigned to select the graph’s categories), helped the investigations go more smoothly. Indeed, evidence of this also surfaced throughout the classroom observations. In particular, elements of graph setup that did not occur in advance (e.g., using the tablet’s camera to take personalized category photos), but instead required an in-the-moment process, seemed to be unexpectedly challenging for teachers. They tended to become flustered when those situations arose, and their students tended to become fidgety or distracted from the task at hand.

Finally, observational data also highlighted the app’s technical limitations. For example, to create a graph in the app, users must include a minimum of two and a maximum of seven categories. These parameters were in place to make created graphs functional and visually discernible, yet occasions arose when teachers attempted to graph either only one category of data or eight or more categories and were unable to do so. In addition, in this version of the app, the graph’s range was not changeable after its initial selection, and thus an initial range selection of 0–10 could not be changed later if one graph category needed to contain 11 or more data points. This was observed to be an issue when data points represented individual students or student votes and more children belonged to a particular category than the teacher expected. To accommodate this, an editable range has been integrated into the latest version of the app.

8. Discussion

8.1. Summary of findings

It is important for young children to have lots of opportunities to think systematically about questions and answers that are relevant to their lives and interests. Current research suggests that preschool children can engage with data, and that data learning provides an important context for solving larger problems and answering meaningful questions. Moreover, to build a solid basis for problem-solving skills later in life, children ages 4 through 5 need early, introductory experiences both to learn and to practice mathematics and computational thinking skills (Bers, 2008; Gelman & Brenneman, 2004). The current study provides evidence that an intervention (curricular investigations and the *Preschool Data Toolbox* app) can scaffold the problem-solving process and support specific data collection and organization steps (collecting, recording, representing) while providing teachers with tools and resources that are developmentally appropriate, engaging, and easy to use. Teachers seamlessly integrated the intervention into their existing preschool curricula and routines, such as circle time and question of the day, providing further evidence of the usefulness of the tools and resources for early childhood classrooms.

Importantly, the intervention helped teachers become more comfortable with teaching DCA and increased their confidence that preschoolers can and should engage with this content. While not a specific goal of the intervention, teachers grew in their comfort with using technology to teach generally and to teach mathematics specifically. This finding is an interesting one, as early childhood teachers’ attitudes toward mathematics are often negative (Bates, Latham & Kim, 2011). In fact, teachers commonly say that they *chose* to teach preschool based on the belief that teaching mathematics was not a requirement of early childhood education (Ginsburg, Duch, Ertle & Noble, 2012; Lake & Kelly, 2014). Therefore, a DCA intervention that also promotes teachers’ positive attitudes toward technology and mathematics is worth emphasizing. By providing a supportive structure for teachers that breaks down the complicated task of teaching preschoolers DCA skills into smaller steps, the intervention also supported children’s problem-solving by structuring the investigation and computational thinking process. In this way, the technology was educative for both the teacher and the children. The app was a tool that scaffolded the parts of the investigation process that teachers often find more challenging, creating visual data displays and supporting children to interpret data. In addition, because the app itself was designed with early childhood teachers in mind, the interface allowed teachers to successfully use and navigate the technology during instruction in preschool classrooms.

Teachers perceived their students to improve in their learning and consistently reported that children's ability to ask research questions, collect and organize data into graphs and charts, to use these representations to understand the data, and to answer the original question, grew over the course of the study. As both teachers' and children's comfort, knowledge, and skills related to DCA increased over the course of the study period, there were multiple opportunities for children to take on larger, more independent roles within investigations, and this unfolded naturally. Importantly, independent child assessment findings showed that participating children improved in their foundational mathematics skills (i.e., counting, sorting) and that they learned new mathematics and CT skills, such as understanding visual representations of data. Teacher interviews concur with this conclusion as teachers perceived that the intervention had a positive impact on children's learning as they gained experience using computational tools to create visual data displays and interpreting data to solve problems.

The app provided several affordances to teachers as they engaged children in learning activities. In particular, the app helped to scaffold the DCA process and make the creation of graphs quick and engaging for children, allowing the teacher to focus on viewing and discussing the data, and ultimately, helping children to develop deeper conceptual knowledge. Navigation with the app was easy and app features were valued, such as the sorting and drawing features. We have found in our work that teachers often spend more time creating data displays and not enough time discussing or analyzing the data, so providing tools that support class discussions around data are particularly valuable. Teachers consistently appreciated that the app freed up their instructional time from the creation of data visualizations allowing for interpretation and use of data in meaningful ways. In addition, data displays are often difficult for young children to generate on their own, but by the end of the study, children were able to ask research questions of their peers and enter the data in the app to create displays that could be interpreted during discussion time. The *Preschool Data Toolbox* app therefore helps teachers facilitate problem-solving with data by allowing children to more easily compare data, make observations, and interpret findings, which is in accordance with Brownell's (2014) suggestion that young children should spend approximately one-third of the time in data collection and the remaining two-thirds engaged in comparing parts of the data visualizations and drawing conclusions through discussion with adults. Importantly, the trajectory of the investigations leveraged the growing comfort and skills of the teachers and students to integrate DCA practices into classroom instruction, and the ease of use of the app engaged children in DCA in additional curricular topics, outside of mathematics. That is, teachers and students gained experience with how and why to engage in problem-solving with data through structured curricular investigations. This comfort with using a data collection and analysis process and the ability to use the app to create data displays as part of the open-ended *Create Your Own* investigation provided teachers with the opportunity to make DCA a part of their regular instructional practice. Finally, children were encouraged to consider how problem-solving with data could help them to answer their own research questions and tell a detailed story about a topic or theme of interest. As children's comfort with collecting, organizing, and discussing data grew, they were able to take a more active role in the investigation process. The investigations built upon children's curiosity and provided children with a level of autonomy that helped them to be more engaged in their own learning.

The scope and sequence of the *Preschool Data Toolbox* activities were designed to foster student-led inquiry-based investigations. The goal of these investigations was to help children to identify and pose research questions; pursue answers to their questions; and then use the app to record, organize, and display the data. Our findings revealed that the *Create Your Own* and *Design a Data Story* investigations were positively received by teachers, but they posed some challenges for teachers to enact in practice. In particular, the findings showed that when teachers generated their own research questions (Create Your Own), teachers typically fell back on instructional routines that were familiar, such as posing a "Question of the Day" and using the app to graph simple data. For these teacher-led investigations, we found that teachers often utilized the app and data collection and analysis process but focused less on higher-order mathematics learning goals. Their investigations were typically based on counting data or creating tally charts and were not necessarily based on answering deeper questions of interest to children or questions that required a data visualization to answer. Interestingly, these teacher-generated investigations also did not require a high level of scaffolding.

Despite including sequences of structured investigations that set the stage for more open-ended student-led investigations, the *Design a Data Story* investigations were not observed. Therefore, we believe that implementing the open-ended investigations may require additional supports embedded in the app or additional professional learning supports to increase the cognitive challenge provided to children. While the inclusion of the Design a Data Story to record the investigation process was desirable for teachers, the implementation of the structured investigations were more successful, suggesting the importance of providing teachers with appropriate support to engage in an inquiry process.

Altogether, the intervention highlighted the importance and usefulness of engaging in a problem-solving with data process that includes specific computational thinking and mathematics learning goals and utilizes computational tools to answer questions. Importantly, providing early childhood teachers with the *Preschool Data Toolbox* app and accompanying curricular investigations, supported teachers to engage children in data collection and analysis and promoted children's mathematics learning as compared to a business-as-usual comparison group, The intervention provided teachers with the opportunity to apply new skills and practices tand exposed teachers to an early childhood-friendly technology that fostered their comfort and confidence to engage children in problem-solving with data. Given how seamlessly teachers integrated the *Preschool Data Toolbox* app into their routines and instructional practice, and considering teachers' reports of continuing to use the app and the investigations in the future to support their learning goals for children, we expect teachers to integrate this tool beyond the scope of the study.

8.2. Implications

This study provides initial evidence that the thoughtful use of computational skillsets and digital technologies can deepen children's learning of mathematics and demonstrates the learning potential of integrating learning goals related to data collection and analysis in preschool. By supporting children's engagement with real-world questions and meaningful investigations, children had positive early mathematics outcomes related to data collection and analysis, while simultaneously building flexible problem-solving skills. Research suggests that integrating computational thinking into early mathematics instruction can create powerful learning experiences (e.g., Grover & Pea, 2013; Kazakoff & Bers, 2012). In fact, many of the data-based CT learning goals align well with early mathematics learning goals as evidenced by our learning blueprint and that displaying and analyzing data are both early mathematics skills and components of CT that are appropriate for early childhood (e.g., Bers, 2018; Brennan & Resnick, 2012; Clements, 2007; K-12 Computer Science Framework, 2016). This investigation provided initial evidence that with specifically designed tools and resources such as the *Preschool Data Toolbox* app, early childhood teachers can support early mathematics skills such as collecting and organizing data; using pictures, graphs, and charts to represent and summarize data; and identifying and using relevant parts of the data representations to answer questions. Over time, the goal for children is to work with data in new ways, such as using computational tools to solve problems, that prepares them to engage in other computational thinking practices in the future.

8.3. Future directions

The present study demonstrated that engaging children in problem-solving with data and supporting preschool children's DCA skills can be effective and developmentally appropriate. Children enjoyed engaging in the investigations, particularly when they started taking a more active role in the process as their comfort with collecting, organizing, and discussing data grew. The *Preschool Data Toolbox* app was a helpful scaffold for the steps involved in problem-solving with data and added to the engagement of students and teachers in each aspect of DCA. In the future, it will be interesting to see how the investigations and app are implemented without the supports provided by the study. For example, are the embedded teacher's guide, professional development videos demonstrating use of the app, and the features of the app sufficient to scaffold teachers' use without the support of the research team? Additionally, could the investigations and app be used with early elementary students to support their DCA skills and learning? Furthermore, are there ways that caregivers could be supported in using this app in home contexts?

Finally, the app included places to tailor investigations to the needs and interests of the teacher and students and to fit within the existing themes and curricula of the preschool classroom. This flexibility helped teachers ensure that investigations were relevant and blended data into these other topics, creating a cross-disciplinary set of activities that honored the variety of learning happening in preschool classrooms, including literacy and social and emotional learning. We would love to understand how teachers leverage the app for their purposes, what challenges they face, what additional features might support them in using the app to support their pedagogy, and the resulting learning that occurs when students engage with the app for these varied purposes.

While this study provides evidence of promise for promoting children's mathematics learning and integrating DCA instructional activities into preschool pedagogy, the intervention conditions were not randomized to treatment or control and therefore the generalization of the findings is limited. However, given that early childhood teachers often lack access to high-quality mathematics instructional activities, the investigations and app add to the research literature by providing evidence that problem-solving with data and mathematics learning goals related to DCA can be integrated into early childhood instructional practice. Moreover, the *Preschool Data Toolbox* app and corresponding investigations provide a specific model and resources for integrating data collection and analysis and computational thinking practices into preschool instruction that are educative for both teachers and students and are developmentally appropriate. In fact, given the visual nature of the representation of the data, introducing problem-solving with data and using a digital tool to engage in data collection and analysis with pre-literate children may provide another point of entry to support children's conceptual development. Future studies could investigate the impact of the intervention on teachers' instructional practice and further explore the relation to children's conceptual understandings.

Declaration of Competing Interest

None.

CRediT authorship contribution statement

Ashley E. Lewis Presser: Conceptualization, Methodology, Formal analysis, Resources, Writing – original draft, Funding acquisition. **Jessica Mercer Young:** Conceptualization, Methodology, Formal analysis, Resources, Writing – original draft, Funding acquisition. **Deborah Rosenfeld:** Resources, Writing – original draft. **Lindsay J. Clements:** Methodology, Formal analysis, Resources, Writing – original draft. **Janna F. Kook:** Methodology, Formal analysis, Writing – original draft. **Heather Sherwood:** Formal analysis, Writing – original draft. **Michelle Cerrone:** Formal analysis.

Data availability

The data that has been used is confidential.

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